Astronomy magazine

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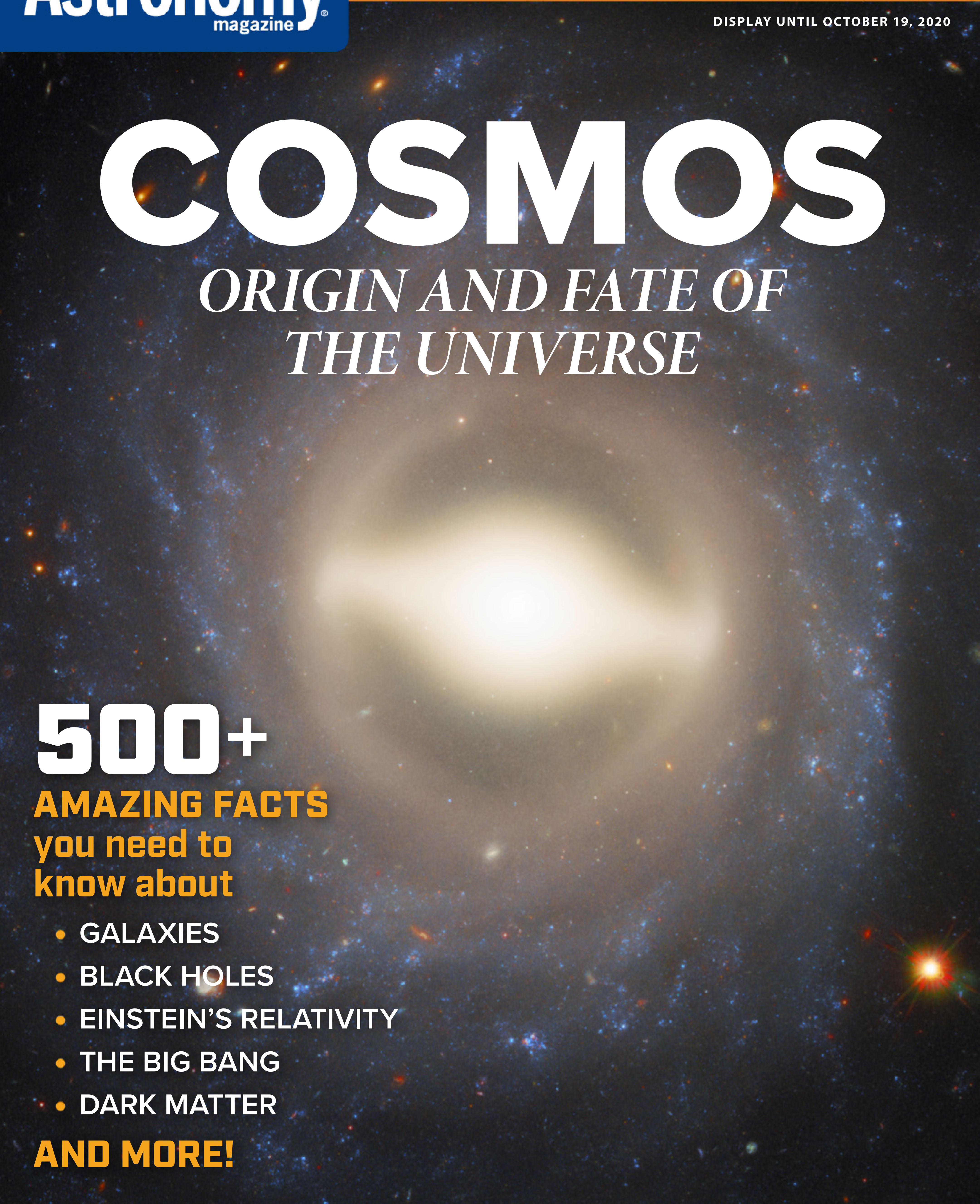

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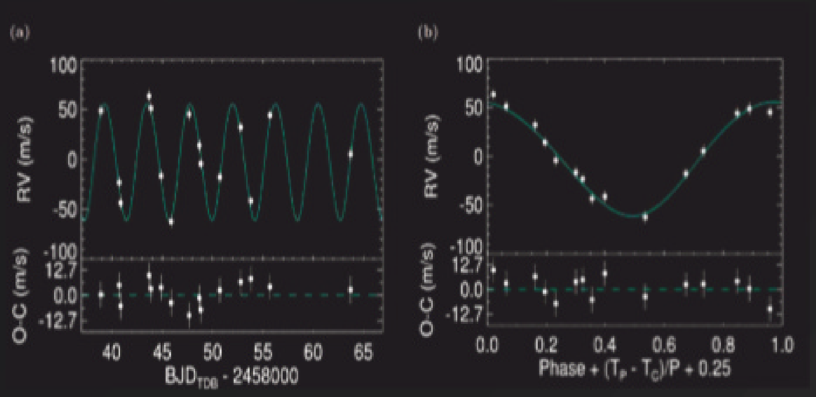

EXO-PLANET RADIAL VELOCITY

This spectroscopic data of the 51 Peg star system shows radial velocities captured and analyzed by the MINERVA team. Utilizing an array of four PlaneWave Instruments CDK700 telescopes at Mt. Hopkins, AZ, the goal of the MINERVA project is to identify and study super-Earths that are located within the habitable zones of the 125 brightest and chromospherically quiet stars visible from Arizona.

WHIRLPOOL GALAXY

Messier 51 captured by Don Elledge, using his PlaneWave Instruments CDK700 at the Villa Stellarum Observatory in Austin, TX. He collected LRGB data using integration times of 7/3.75/3.75/3.75 hours. The resulting 18 hours of data sees well beyond Austin's suburban skies.

CIGAR GALAXY

Messier 82 captured by Kurious George, using his PlaneWave Instruments CDK600 system near Julian, CA. This amazingly deep image results from 35 hours of HaLRGB data, with integration times of 20/6/3/3/3 hours.

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Westerlund 2, located 20,000 light-years from Earth, has some of the Milky Way's brightest, biggest, and hottest stars. NASA, ESA, THE HUBBLE HERITAGE TEAM (STScI/AURA), A. NOTA (ESA/STScI), AND THE WESTERLUND 2 SCIENCE TEAM

CONTENTS

6
From the Editor

8
A universe of galaxies
The universe is awash in islands of matter: Some 100 billion galaxies make up the basic building blocks of the cosmos. **David J. Eicher**

16
Our trillion-galaxy universe
Astronomers have learned that their previous estimate of the number of galaxies in the cosmos was slightly off — by more than 1 trillion. **Christopher J. Conselice**

22
Relativity: Right or wrong?
Einstein's relativity replaced Newton's gravity. Now observations of black holes might test the limits of Albert's masterpiece. **Jesse Emspak**

34
Is the Big Bang in crisis?
Stubborn problems with dark matter, dark energy, and cosmic expansion have some astronomers rethinking what we know about the early universe. **Dan Hooper**

44
Dark matter's shadowy effect on Earth
Earth's periodic passage through the galaxy's disk could initiate a series of events that ultimately lead to geological cataclysms and mass extinctions. **Michael R. Rampino**

50
Supernova 1987A: 30 years later
When a blue supergiant star lit up the southern sky, astronomers used it to learn how massive stars explode. **Liz Kruesi**

56
Pulsars at 50: Still going strong
When astronomers initially stumbled upon these rapidly pulsing beacons in 1967, they thought they had found ET. The truth was almost as shocking. **C. Renée James**

62
Dark stars come into the light
With help from dark matter annihilation, some of the universe's earliest stars were able to grow much larger than they would otherwise. **Mara Johnson-Groh**

70
Why do galaxies align?
The matter in our universe forms filaments and threads like a grand cosmic web, tugging galaxies and clusters into place along the way. **Michael West**

76
Do all galaxies have dark matter?
The discovery of two ghostly galaxies created a hullabaloo in the astronomical community. But the jury's still out on what's really going on. **Jake Parks**

84
Galaxy clusters: The universe's cosmic lenses
With Hubble's superb optics and gravity's magnifying power, astronomers are opening a new frontier at the edge of the universe. **Liz Kruesi**

On the cover

The majestic galaxy NGC 1015, seen in a stunning image from Hubble, is found nestled within the constellation Cetus the Whale, 118 million light-years from Earth.

ESA/HUBBLE & NASA, A. RIESS (STSCL/JHU)

All that ever will be

"The cosmos is all that is or ever was or ever will be," Carl Sagan once said. In the most alluring of combinations, the field of cosmology brings what we know about the universe together in poetic terms — understanding the origin and fate of it all.

In this special package of stories, the editors of *Astronomy* present a walk-through of cosmology, up-to-the-minute and packed with facts, that details the state of the union on our cosmological knowledge.

You'll read about the nature of galaxies, the basic building blocks of the cosmos, and how they contain vast stores of stars, gas, and dust. Our own Milky Way, of which the Sun is but one star, contains some 400 billion suns spread over its diameter of at least 100,000 light-years.

We also explore the recent estimates of the total number of galaxies in the visible universe, a number that stands — at present — at around 100 billion. Yet if we travel back in time, as we do by looking at distant objects in the universe, we see that something like 2 trillion galaxies existed in early times, before many of them merged to make larger galaxies.

Before Einstein, our conception of the universe was Newtonian, based on mechanical physics and forces. Relativity theory turned the cosmos on its head, and for the last century we've been able to understand how the cosmos works in a more sophisticated way — but not necessarily a perfect way. We also examine how cracks in the universally accepted Big Bang theory are forcing cosmologists to wonder about some of its attributes.

Relativity theory turned the cosmos on its head.

Weird, high-energy creatures make up part of the story of cosmology, as well. The most energetic star in our part of the universe, Supernova 1987A, exploded violently a generation ago, shedding light on the deaths of massive stars. We've also celebrated a half-century of understanding pulsars, those rapidly rotating, very dense stellar remnants.

IC 342 offers a grand glimpse of a face-on galaxy. TONY HALLAS

And, of course, where would a package on cosmology be without attention to black holes, dark matter, and massive galaxy clusters? We pack it all in here, and hope you will enjoy reading, and thinking about all that ever was, or ever will be.

Yours truly,

David J. Eicher
Editor

COSMOS
ORIGIN AND FATE OF THE UNIVERSE

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- Maps from the two Viking missions and updated data from the Mars Orbiter Laser Altimeter.
- 206 features identified and labeled, including landing sites.

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A UNIVERSE OF GALAXIES

The universe is awash in islands of matter: Some 100 billion galaxies make up the basic building blocks of the cosmos. **by David J. Eicher**

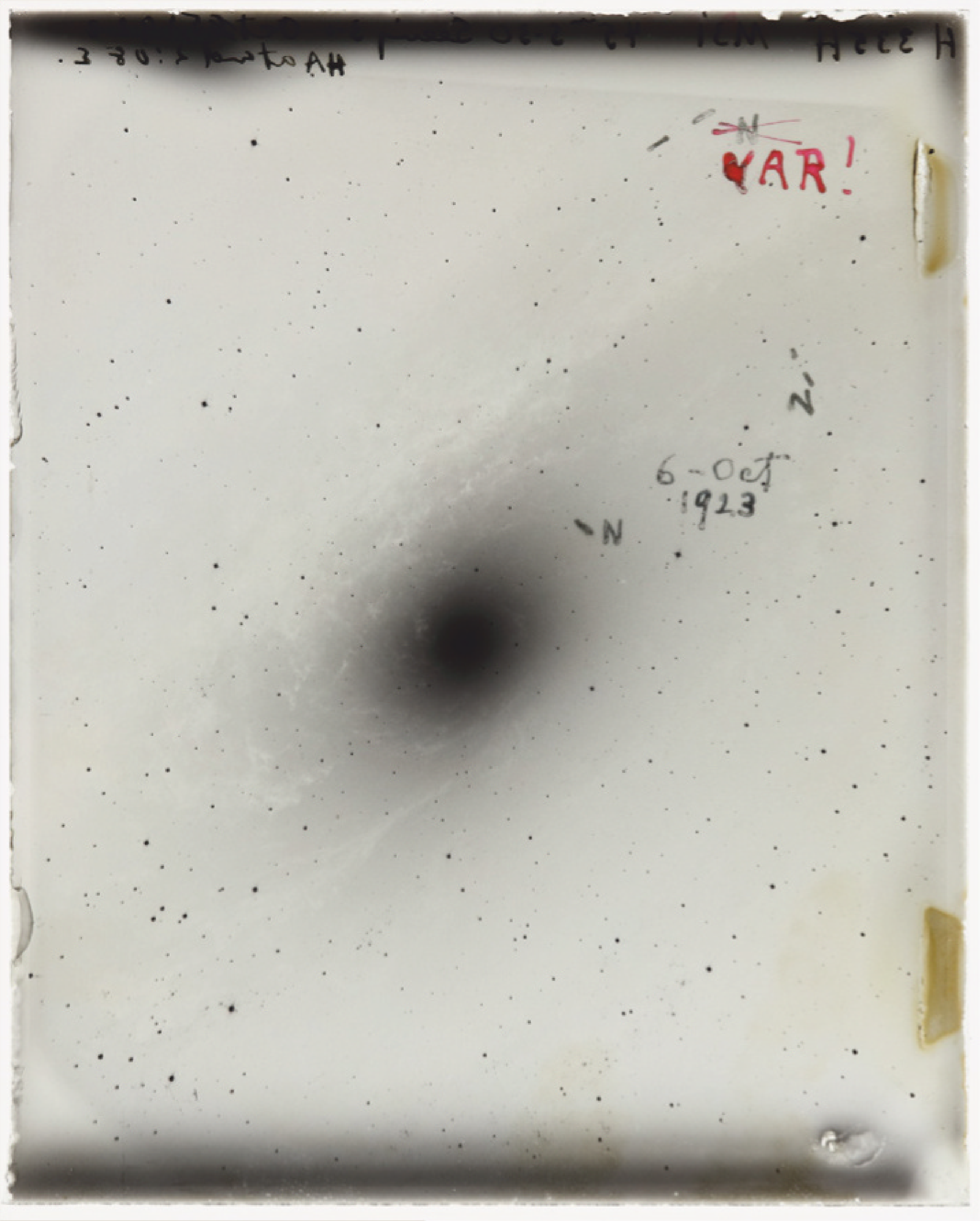
ON THE EVENING of Oct. 4, 1923, near Los Angeles, a young astronomer got into his car and began a motorized trek up to Mount Wilson. There, he arrived at the observatory that housed the 100-inch Hooker Telescope, at the time the largest telescope in the world.

Edwin Hubble was a fourth-year astronomer at Mount Wilson; he enjoyed

Our galaxy, the Milky Way, explodes with color in this image taken in Chile's high Atacama Desert, perhaps the darkest sky on Earth. The semicircular arc of the Milky Way is peppered with bluish and pinkish light from glowing star clusters and nebulae. The Large and Small Magellanic Clouds lie above and to the right of the Milky Way. P. HORALEK/ESO

using the Hooker Telescope because he was interested in, among other things, studying spiral "nebulae." These mysterious gas clouds were scattered across the sky, and no one understood their nature. In the early days of the 1920s, Hubble had assigned himself the task of figuring them out.

He pointed the great telescope toward his favorite object: the nebula in Andromeda, M31. This spiral-shaped cloud is faintly visible to the naked eye under a clear, moonless sky. He then captured its image on a photographic plate. Hubble was excited by the result. On it, he found a suspected nova, an exploding star. The next night, he photographed M31 again, hoping to catch the nova and



ABOVE: Astronomer Edwin Hubble made an exposure of the "Andromeda Nebula" with the Hooker Telescope at Mount Wilson Observatory near Los Angeles on Oct. 5, 1923. He was initially excited, believing he had recorded a nova, an exploding star. He marked the star, which lies between two tick marks he drew at the top right on the plate, with the letter N. The star turned out to be a Cepheid variable, and Hubble used it to prove that the distance to the Andromeda Galaxy was far greater than astronomers thought. COURTESY OF THE CARNEGIE OBSERVATORIES/CINDY HUNT

record it under better atmospheric stability. The second plate did indeed record the nova, but little did he know, he also had captured a plate that would become legendary in the history of science.

His observing time over, he returned to his office to analyze the catch. Suddenly, Hubble made an astonishing realization: The nova was not a nova at all, but a particular type of star that changed its brightness, a Cepheid variable. Checking earlier plates, he was able to confirm that, and he realized that the star's faintness had incredible implications.

The star, and the nebula that encompassed it, must lie at a distance of a million light-years — three times larger than anyone at the time believed the size of the whole universe to be. Today, thanks to improved measurements, astronomers know the object is 2.5 million light-years away.

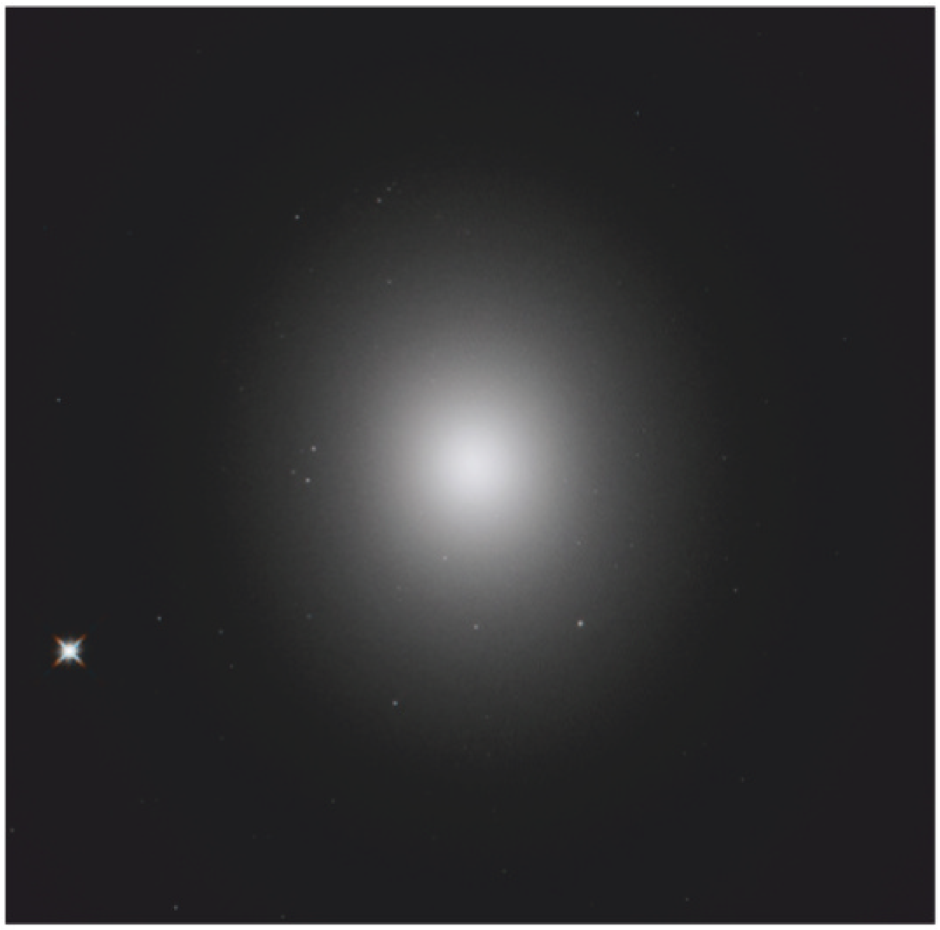
Aided in part by earlier work done by Vesto M. Slipher and by his own colleague, Milton Humason, Hubble had at once discovered that the universe was far larger than anyone had believed, and that spiral nebulae like Andromeda were actually distant galaxies. They were whole systems of stars and gas, separated from our own Milky Way by a long hike.

At Arizona's Lowell Observatory, as early as 1912, Slipher had recorded the apparent velocities of spiral nebulae and, with the work now done by Hubble, it was clear the universe was expanding — the galaxies were flying apart from one another over time. The universe was not only far larger than anyone had previously believed, but it was growing as time went on.

By 1929, astronomers had put a cosmic picture of the past together. If you traced the histories of many of the galaxies backward in time, it meant that the cosmos began with a small, infinitely dense point at its origin. This research was an extension of work originally done by Belgian astronomer Georges Lemaître. Astronomers understood this cosmic point of origin, later called the Big Bang, as the start of the universe, and it must have occurred billions of years ago, they calculated. The Big Bang had commenced the expansion that was driving all the galaxies away from each other as time rolls on. The whole universe seemed to be flying apart.

In the 1930s, Hubble began to study and classify galaxies into their various so-called morphological types, the array of structures astronomers saw in photographs. He eventually assembled the

RIGHT: Perseus A, also called NGC 1275, is an eruptive galaxy at the core of the Perseus Cluster, which is made up of some 1,000 galaxies about 240 million light-years away. The dominant member of the Perseus Cluster, Perseus A is a Seyfert galaxy with an active nucleus, powered by a 340-million-solar-mass black hole in its core. HUBBLE LEGACY ARCHIVE, ESA, AND NASA



CLOCKWISE FROM TOP LEFT: Elliptical galaxies like M49 in Virgo are huge spheres of stars that float in an ellipsoidal cloud. Although their diameters are often similar to large spiral galaxies, they can hold vastly more mass because they are shaped like a football rather than a disk. This galaxy lies some 56 million light-years away and is one of the more massive galaxies in the Virgo Cluster. NASA/ESA/STScI

The beautiful spiral galaxy NGC 2403 in the northern constellation Camelopardalis is close to us, lying some 11 million light-years away. It is an outlying member of the M81 Group, which contains the bright and well-observed galaxies M81 and M82 in Ursa Major. TONY HALLAS

One of the greatest edge-on galaxies in the sky, and the one most people say looks like a flying saucer, is the Sombrero Galaxy (M104) in Virgo. It consists of a great rotating disk with a prominent dust lane edging it, consumed by a glowing halo of gas and stars. It lies 43 million light-years away and is about half the size of the Milky Way, sporting a diameter of 49,000 light-years. NASA AND THE HUBBLE HERITAGE TEAM (AURA/STScI)

types of galaxies he observed into a tuning fork-shaped diagram. It contained spiral galaxies, barred spiral galaxies — spirals containing a linear "bar" of material passing through their centers — lenticular (lens-shaped) galaxies, and elliptical galaxies. He also identified irregular galaxies, clouds of stars and gas that lacked an organized shape. Later on, astronomers identified peculiar galaxies, systems that appeared to be wracked with explosive or disruptive events. They also identified a class of galaxies called dwarf spheroidals, which seemed to be numerous in the local universe.

By the 1950s, French astronomer Gérard de Vaucouleurs of the University of Texas had expanded Hubble's classification scheme into a more complex system that took into account many observed properties of galaxies. De Vaucouleurs produced a pseudo-three-dimensional plot showing the galaxies' relationships, nicknamed the "Cosmic Lemon" due to its shape. De Vaucouleurs included details on bars in galaxies, descriptions of rings of matter visible in them, and an evaluation of how loosely or tightly the spiral arms of a galaxy were wound. He also included evaluative details about the nature of irregular and peculiar galaxies.

The last generation of extragalactic astronomy has moved into far more sophisticated analyses than cataloging. By using the Hubble Space Telescope, astronomers have estimated that some 100 billion galaxies must exist in the cosmos. And the number may be much greater than that. Probably some 2 trillion galaxies existed in the early universe, but it seems clear that galaxies near each other are drawn together by gravity and

CLOCKWISE FROM TOP LEFT:
At 11 million light-years away, IC 342 is a close galaxy. It's also a member of a loose group along with several others. IC 342 has a low surface brightness and lies in Camelopardalis, near the plane of the Milky Way in our sky. So it's a little difficult for amateur astronomers to spot, despite its elegant form.
TONY HALLAS

The weirdly distorted elliptical galaxy NGC 474 in Pisces lies at a distance of 100 million light-years. The neighboring spiral galaxy NGC 470 lies just above it. Multiple shells and tidal tails surround NGC 474, caused by interactions with its neighbors and by density waves that propagate through the medium. This mammoth object stretches 250,000 light-years across — two and a half times the diameter of the Milky Way. P-A. DUC (CEA, CFHT), ATLAS 3D COLLABORATION

The Whirlpool Galaxy in Canes Venatici, another galaxy near the Big Dipper, is also known as M51 and is a top telescope target. An interacting pair of galaxies, the Whirlpool is being passed by a little interloper, NGC 5195, which is drawing material off one of the larger galaxy's spiral arms. The pair lies 23 million light-years away, and M51's disk stretches across 60,000 light-years. TONY HALLAS

NGC 4565 in Coma Berenices is the brightest and most prominent galaxy in our sky that is oriented perfectly edge-on to our line of sight. We see its disk as a thin, silvery needle. Some 57 million light-years off, it lies in the Virgo Cluster and has a prominent central bulge, suggesting it may be a barred spiral.
ADAM BLOCK

combine over cosmic time. Despite the universal expansion, then, normal galaxies like the Milky Way are probably made of dozens or more protogalaxies that merged into larger systems. You can see these primitive blobs of matter, bluish protogalaxies, in the early universe within the Hubble Ultra Deep Field pictures.

Our own galaxy

As astronomers have studied greater numbers of galaxies over the past few decades, they've discovered many things, but one that is impossible to ignore is that the universe is incredibly large. If you look at a galaxy in your telescope's eyepiece tonight, the photons striking your eye have been traveling at the fastest speed there is — 186,000 miles per second (300,000 kilometers per second). Nonetheless, they have taken 2.5 million years at that velocity to reach us from the Andromeda Galaxy. And that object is nearly on our cosmic doorstep.

Of course, the knowledge of our own galaxy, in a primitive sense, goes back to antiquity. The name Milky Way comes from the Latin *via lactea*, which derives from the original idea, the Greek term, *galaxías kýklos*, "milky circle." The band of Milky Way visible in our sky, most

prominently in the summer and winter evenings, is the unresolved light from billions of stars lying along the plane of our galaxy.

But only in the past few decades have we come to understand that the Milky Way is one of the 100 billion galaxies in the universe, and that its disk stretches some 100,000 light-years across. It contains some 400 billion stars, although we don't know exactly how many because dwarf stars are faint and difficult to see over long distances. For decades, astronomers believed the Milky Way was a simple spiral galaxy. But studies in this century have shown the Milky Way is a barred spiral, and that our Sun and solar system lie some 26,000 light-years from the center, in one of the galaxy's arms.

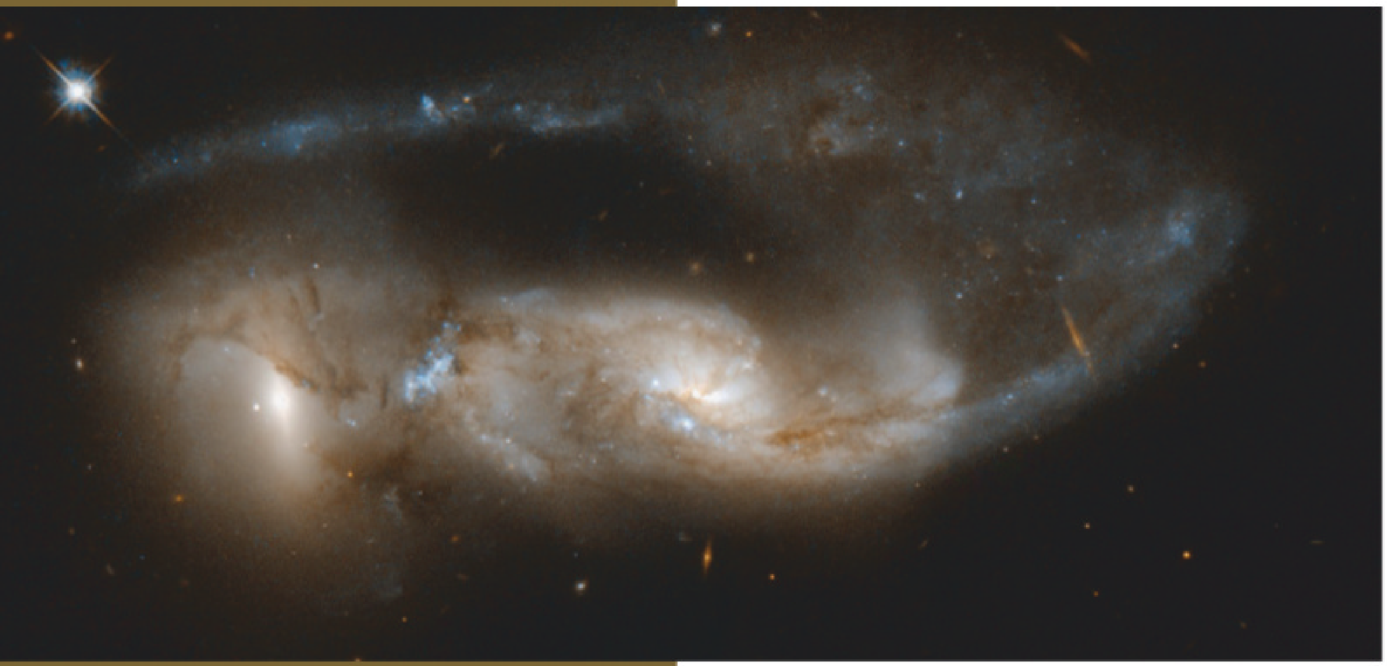
The Milky Way consists of a bright disk, a slowly spinning platter of stars and gas that contains most of the stars we see. Our Sun orbits the center of the galaxy once every 220 million years, meaning that we've rotated around the galactic center about 20 times since the formation of the solar system. Far away, in the center of the galaxy, lies a supermassive black hole containing around 4.3 million times more mass than the Sun. In recent times, astronomers have discovered that supermassive black holes in the centers of galaxies are the norm. Nearly all galaxies, except for dwarfs, have them.

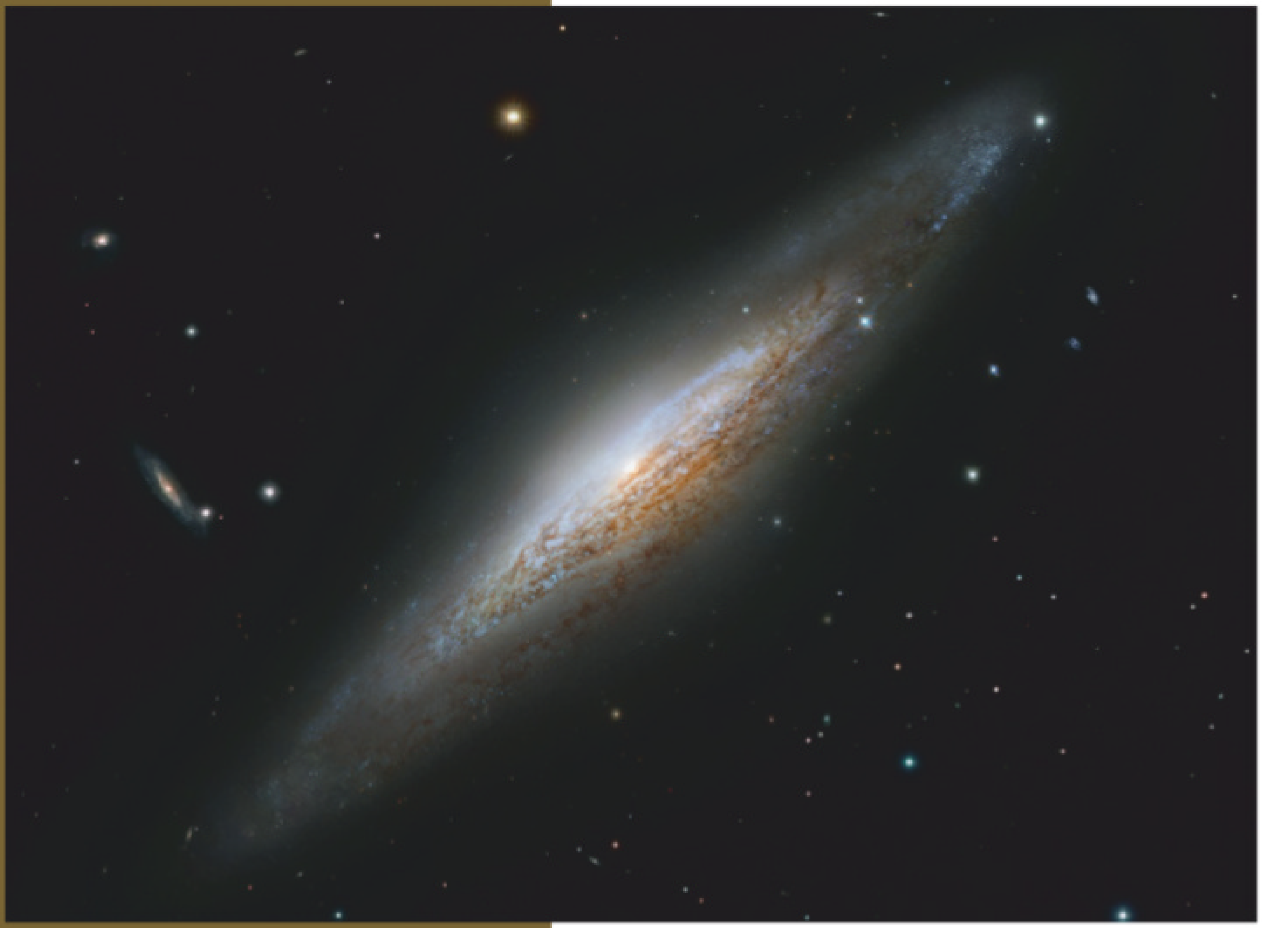
The galaxy's disk is encapsulated by a halo of a small number of stars, along with huge spheres of ancient stars called globular star clusters, and a big envelope of dark matter. Astronomers don't yet know what dark matter consists of, but they know it is there because of the gravitational influence it has on the visible matter they can observe.

The Local Group

The Milky Way is hardly alone in the cosmos. It belongs to a group of at least 54 objects called the Local Group of galaxies, a name Hubble gave to this local cloud of objects as he mapped the nearby cosmos. The primary members of the Local Group are the Milky Way, the Andromeda Galaxy, and the Pinwheel Galaxy (M33). But each of these big three spirals has a cloud of attendant galaxies, too. The Milky Way's satellites include the Large and Small Magellanic Clouds, visible to the naked eye in the Southern Hemisphere, and many dwarf galaxies. The diameter of the Local Group is about 10 million light-years, some 100 times the diameter of the Milky Way.

And moving outward into the deeper universe, we encounter more examples of those 100 billion galaxies. These majestic islands of stars and gas exist in groups, like our Local Group, but also in larger assemblages called clusters and very large ones called superclusters. Despite the overall expansion of the universe, meaning that most galaxies are moving away from each other as the cosmos grows,





TOP: Two distorted galaxies in Draco are locked in a tidal embrace: NGC 6622 (left) and NGC 6621, collectively known as Arp 81. This composite image reveals twisted streams of gas and stars, chaotic star formation, and a massive tidal tail stretching across the top portion of the picture. The tail measures 200,000 light-years across, twice the diameter of the Milky Way. These galaxies lie at a distance of 280 million light-years. HUBBLE LEGACY ARCHIVE, ESA, NASA, MARTIN PUGH

ABOVE: A slender needle of light, spiral galaxy NGC 2683 in Lynx is oriented nearly edge-on to our line of sight and makes a wonderful telescopic target. It may be a barred spiral; galaxies aligned like this are hard to classify because we can't see their disks well. The galaxy, which lies some 20 million light-years away, has a remarkably bright core due to a large population of old, yellowish stars. SUBARU TELESCOPE (NAOJ), HUBBLE SPACE TELESCOPE, ROBERT GENDLER

gravity keeps smaller numbers of galaxies bound to each other on their journeys. Our Local Group, for example, is a member of the so-called Virgo Cluster of galaxies, named so because its richly populated center lies in the constellation Virgo in our sky.

The Virgo Cluster contains at least 1,500 galaxies and is centered some 54 million light-years from Earth. You can see some of the brightest galaxies near the core of the Virgo Cluster in amateur telescopes, in an array called Markarian's Chain. This line of galaxies contains supermassive elliptical galaxies such as M84 and M86, and a variety of spiral galaxies, too. For backyard astronomers, this playground of galaxy types is one of the really entrancing areas of the sky, and it is best visible on springtime evenings under clear, moonless conditions.

Most of the Virgo Cluster galaxies contain supermassive black holes in their centers. M87 is quite an example. Whereas the Milky Way's central black hole weighs in at 4.3 million solar masses, the colossal black hole inside M87 contains an estimated mass of 5 billion to 7 billion suns, some 1,000 times more massive than ours. M87 is one of the largest galaxies in our part of the universe — it is a so-called cD galaxy, short for centrally dominant — and it has "eaten" many of the smaller galaxies that once surrounded it. That's what massive galaxies do — they consume their neighborhood partners.

Superclusters

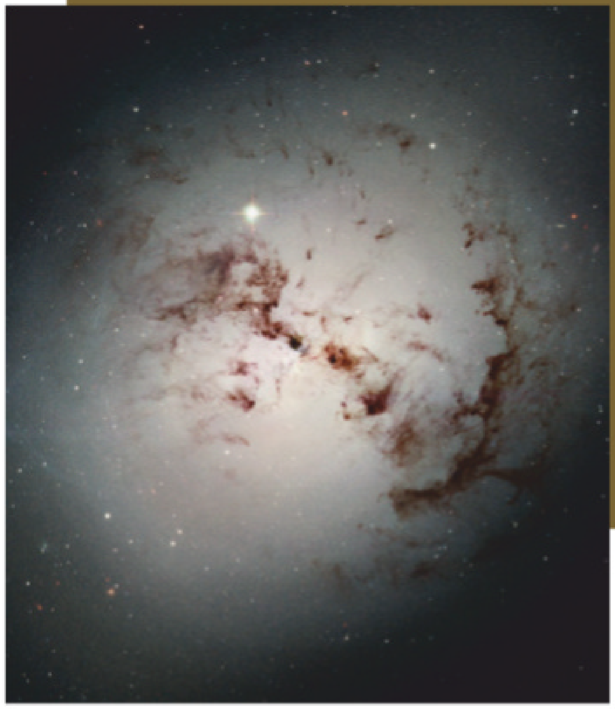
A cluster containing 1,500 galaxies is one thing, but much larger assemblages of galaxies also exist. The Virgo Cluster itself is a member of the so-called Virgo Supercluster, or Local Supercluster, which holds thousands of galaxies on a scale an order of magnitude larger yet. The Virgo Supercluster holds our Milky Way, the Local Group, the Virgo Cluster, and altogether some 100 galaxy groups and clusters. This amazingly large framework stretches some 110 million light-years across, and it is one of about 10 million superclusters that make up the entire cosmos.

Despite the huge number of galaxies existing in the Virgo Supercluster, astronomers now know that most of the space in this volume is essentially empty, consisting of great voids. The diameters of these voids range from dozens to hundreds of millions of light-years. Filamentary chains of galaxies wind their way around the dark voids. On large scales, galaxies in clusters and superclusters are like soap bubbles, with galaxies coating the surfaces and voids lying in between.

By the end of the 1980s, astronomers had identified the Great Wall, a sheet of galaxies measuring 500 million light-years across. More recently, the Sloan Digital Sky Survey uncovered the Sloan Great Wall, an assemblage of galaxies at least twice the size of the Great Wall, which covers a long dimension of some 1.4 billion light-years.

LEFT: M83, a magnificent barred spiral galaxy in the southern constellation Hydra, is often called the Southern Pinwheel Galaxy. It resembles the Milky Way in overall form but is considerably smaller, spanning only 60,000 light-years. Hubble captured this close-up portrait of the center of M83, which floats majestically in space some 15 million light-years away. NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STScI/AURA)

BELOW: The strange, distorted galaxy NGC 1316 — known as Fornax A because it was the first radio source discovered in that constellation — is a highly chaotic barred spiral galaxy that looks more like an elliptical. It appears to have been built up by repeated mergers some 3 billion years ago. The strong radio emission comes from a powerful central black hole. The dusty lanes circling this galaxy are witness to the disruptive forces within it. Fornax A lies 62 million light-years away. NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STScI/AURA)



As astronomers discovered more and more distant galaxies, they found that some large mass seemed to be tugging on the local universe, pulling us in the direction of the southern constellations Triangulum Australe and Norma. Called the Great Attractor, this anomaly — some 200 million light-years away — puzzled astronomers. They eventually discovered that an even larger mass in that direction was pulling us. This mammoth structure, called the Shapley Supercluster, is 650 million light-years away and contains the greatest concentration of galaxies in our local part of the cosmos.

The big picture

Additional surprising discoveries have occurred, too. In 2014, astronomers identified a new supercluster based on the relative motions of galaxies analyzed in a more sophisticated way than ever before. University of Hawai‘i astronomers concluded that the Laniakea Supercluster exists, and named it after the Hawaiian word for “immense heaven.”

Laniakea, which is also sometimes called the Local Supercluster, contains some 100,000 galaxies, including the Local Group and the Milky Way. This massive cluster and all its members are traveling together through space, but not all of the galaxies within it are gravitationally bound. Some will splinter apart from the rest of the cluster as time rolls on.

The Laniakea Supercluster has four major components — the Virgo Supercluster, the Hydra-Centaurus Supercluster, the Pavo-Indus Supercluster, and the Southern Supercluster. Altogether, Laniakea contains around 500 galaxy clusters and groups. And surrounding Laniakea in the local universe are other galaxy superclusters — the Shapley Supercluster, the Hercules Supercluster, the Coma Supercluster, and the Perseus-Pisces Supercluster. Each of these structures holds hundreds of galaxy clusters and are linked by the fabriclike web of cosmic structure.

And beginning in the 1980s, astronomers found evidence of structures even larger than superclusters. At first, objects now called Large Quasar Groups (LQG) baffled astronomers. In 1982, Scottish astronomer Adrian Webster found what would become known as the Webster Large Quasar Group, a collection of five quasars stretching over 330 million light-years. Now, nearly two dozen LQGs are known. A structure known as the Huge LQG contains 73 quasars over a diameter of some 4 billion light-years. This massive structure, dismissed by some astronomers, may hold the title as the largest collection of related matter in the cosmos.

Truly, the universe is so big that it’s hard to comprehend. On one hand, the enormity of the universe makes us feel small. Our brief lives happen so quickly, and we wink out, mostly unaware of the incredibly large cosmos around us. But the fact that we are sentient, that we can ponder the stars and galaxies far away from us, makes life in the universe a truly amazing thing. And we’re just starting to get to know the immense world of galaxies.

David J. Eicher *is editor of* Astronomy. *His book,* Galaxies: Inside the Universe’s Star Cities *(Penguin Random House) is available from www.MyScienceShop.com.*

Our trillion-galaxy universe

Astronomers have learned that their previous estimate of the number of galaxies in the cosmos was slightly off — by more than 1 trillion.

by Christopher J. Conselice

HOW MANY GALAXIES EXIST IN THE UNIVERSE? No one knows, but for a generation, astronomers have believed 100 billion was the answer. Now, we've discovered the number is likely much higher.

It's a perplexing puzzle to take on, because the universe is so large and has evolved so much over its 13.8-billion-year history. For many of us, it's a problem that at first may seem as difficult as counting all the grains of sand on all the beaches on our planet. Like many others before and since, when I was growing up near the coast of Florida, I would often sit on the beach and admire the vast amount of sand before me. I would naturally ask myself, "How many grains of sand are there on this beach?" The number seemed almost infinite, or at least

Ten thousand colorful galaxies at wavelengths spanning the near-infrared to the far-ultraviolet populate this image from the Ultraviolet Coverage of the Hubble Ultra Deep Field (UVUDF) project. The UVUDF campaign has compiled the most comprehensive image of our universe to date.

NASA, ESA, H. TEPLITZ AND M. RAFELSKI (IPAC/CALTECH), A. KOEKEMOER (STScI), R. WINDHORST (ARIZONA STATE UNIVERSITY), AND Z. LEVAY (STScI)

Shredded by interaction with a more compact galaxy, UGC 10214 — the "Tadpole" — sits against a colorful backdrop of distant galaxies. With an exposure time just 1/12 of the Hubble Deep Field's, it still reveals galaxies from the very early universe. NASA, HOLLAND FORD (JHU), THE ACS SCIENCE TEAM AND ESA

Most everything else in the universe is within a galaxy, so knowing how many exist is a fundamental property from which the counts of all other things must follow.

incalculable to a young child. When I considered that there were similar beaches all around the world, the number of grains seemed indeed immeasurable.

In fact, this relates to a famous question that the Greek astronomer Archimedes answered. Archimedes, however, didn't limit himself to Earth, but wanted to answer the question of how many grains of sand would fill the entire universe. Of course, Archimedes believed in a much smaller universe than we do today — only a few light-years in diameter. He concluded in "The Sand Reckoner," one of the earliest examples of a research paper, that you would need approximately 10^{62} grains of sand to fill his universe.

Our interests do not change. Ever since Archimedes' time, it is clear that counting things fascinates people. We always want to know "how many" or "how much." And perhaps the most fundamental astronomical counting question is, "How many galaxies are there in the universe?" This is because galaxies are basic units of the universe's matter, and in a real sense they fill the universe, neatly corresponding to Archimedes' grains of sand. Most everything else in the universe is within a galaxy, so knowing how many exist is a fundamental property from which the counts of all other things must follow.

Answering this question further sheds light on many aspects of the universe, such as its cosmological makeup, the nature of the evolution of its structure, and other questions about dark matter and the light from the background sky. The answer also reveals whether galaxies started small and became larger, or whether they formed with masses similar to those we have in the modern universe.

To answer these questions, astronomers must not only determine how to measure the number of galaxies, but also what exactly this measurement means.

Nearly 3,000 galaxies at varying distances appeared in the original Hubble Deep Field, obtained in 1995 over the course of 10 days. This image gave astronomers their first glimpse at the numerous small, irregular galaxies that filled the young universe. R. WILLIAMS (STScI), THE HUBBLE DEEP FIELD TEAM AND NASA/ESA

How do I count thee?

So, how do astronomers measure the number of galaxies in the observable universe? Simple — by counting them. Of course, we have to probe very deeply, going back in time to see the first galaxies and then observing everything in between, which is not as easy as it may sound. The best instrument for this has been, and still remains, the Hubble Space Telescope.

No other telescope in the past 30 years has changed our view of the universe like the Hubble Space Telescope. This is especially true for the study of galaxies, and how they have formed and evolved since the early universe. Because of this ability, Hubble also plays a key role in our story of determining how many galaxies exist in the universe.

The only way to get to these first galaxies, and therefore to count them, is to take very deep exposures. This idea was always part of the Hubble project. In the early days of the telescope, however, astronomers thought that taking a deep picture of a blank field would be a waste of time. They reasoned that the idea behind galaxy formation, based on our current understanding of cosmology, predicts that galaxies should form very late in the universe, near our own epoch of time. If that were true, then a deep picture would come up mostly blank, simply because there would be no galaxies to detect.

Luckily, this did not deter Robert Williams. As the director of the Space Telescope Science Institute, he used his discretionary time in 1995 to carry out a deep pointing of a single area of the sky over two weeks. The result of this was a deep field image, appropriately called the Hubble Deep Field, which probed the universe to a much greater extent than we could ever see before.

To understand why this image is so valuable, think of looking up at the sky to count how many stars are visible. From a dark location, this may seem like a huge number to some people — perhaps millions or even billions. Of course, the answer is actually much smaller. In fact, the number of stars you can see from even the darkest site by eye is only a few thousand. This is similar to the number of McDonald's restaurants on the West Coast of the U.S., which may either seem like not so much, or way too many!

Take a telescope to that dark location, however, and the number of stars we can see increases. Telescopes can gather much more light than the human eye, dramatically increasing the number of stars visible. This concept is similar to the result obtained by the Hubble Deep Field. By pointing a telescope better than any on Earth at a "blank" piece of sky, astronomers discovered many more galaxies than had ever been seen before.

The total area of the Hubble Deep Field is, however, very small, just a few arcminutes on a side in the constellation Ursa Major, near the Big Dipper. Still, this deep exposure revealed several thousand galaxies. That may not sound like many, but extrapolating this result over the entire sky gives us the total number of galaxies we could observe — 100 to 200 billion.

Even at that time, astronomers suspected this was an underestimate. If we were to go deeper, we knew we likely would see even more galaxies.

Adding other wavelengths

Over the next 15 years, deeper and wider surveys obtained better data that increased the total number of galaxies by only a small amount. This was because it was hard to expose longer than the Hubble Deep Field. However, one thing had changed. Astronauts on servicing missions using the space shuttle installed better cameras on Hubble, capable of wide-area, near-infrared imaging. This let us probe in more detail how many galaxies of different masses existed all the way back to when the universe was only a billion years old.

In 2009, astronauts installed the Wide Field Camera 3 (WFC3) during the fifth and final Hubble servicing mission. WFC3, the most advanced camera ever on Hubble, takes very deep pictures of the universe over relatively large areas of the sky at infrared wavelengths. This addition to our astronomical toolkit allowed us to determine the distribution of galaxy masses and answer the questions: Are there more low-mass or high-mass galaxies in the universe? Does this distribution change over cosmic time?

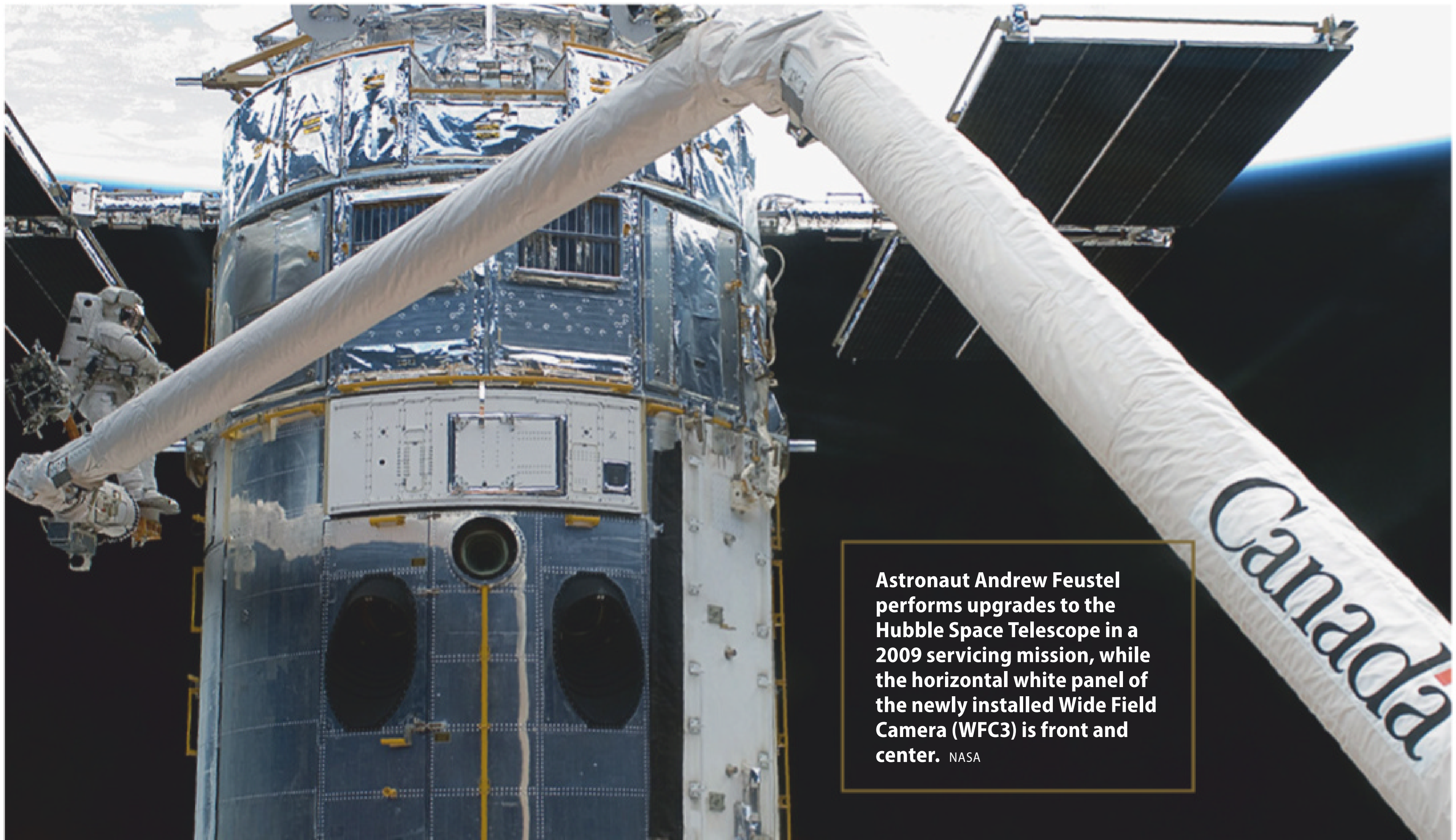
What we get from imaging the cosmos, however, is a 2-D picture of distant galaxies that doesn't show their distribution in time or space. What we need to know is how massive these galaxies are and where in space each one is located.

We can determine this by observing galaxies at many wavelengths. Various types of stars emit light in different parts of the spectrum, so by

UNDERSTANDING PHOTOMETRIC REDSHIFT

The photometric redshift method can be understood quite simply by taking the example of a single hot star that emits as a perfect blackbody. The temperature of the star determines the shape of this blackbody and where the peak of emission is located. Hotter stars have shorter-wavelength peak emission. If this star were placed at a greater distance and thus was part of the expanding universe, the peak of the emission would appear to shift to redder and redder wavelengths as it got more distant, due to the Doppler effect.

Measuring photometric redshifts works the same way, where with many different fluxes at different wavelengths, we can figure out the intrinsic spectrum of a galaxy. Then, by comparing the true spectrum with the actual viewed spectrum, we can determine how much it has been shifted, and thus measure the galaxy's radial velocity and distance. —*C.C.*



Astronaut Andrew Feustel performs upgrades to the Hubble Space Telescope in a 2009 servicing mission, while the horizontal white panel of the newly installed Wide Field Camera (WFC3) is front and center. NASA

GAUSSIAN AND POWER-LAW DISTRIBUTIONS

In a Gaussian distribution, also called a normal distribution, the most common values occur around a single value (the mean), with no bias toward higher or lower values. Examples of normal distributions include the heights of people in a group or students' grades on a test. When a Gaussian distribution is graphed, it has a central "bump" at the mean and edges that trail off symmetrically in either direction. Because this curve is shaped like a bell, it's often called a bell curve.

Power-law distributions describe situations in which some probabilities are much more likely than others. When comparing two quantities that show a power-law relationship, a change in one quantity results in a change in the other quantity as a fixed power of the first. A power-law distribution looks like a steeply curved line when graphed. Power-law distributions occur frequently in physics, as well as economics and biology.

—Alison Klesman

examining the light from a galaxy at each wavelength throughout its spectrum, we can measure the stellar populations within the galaxy. Additionally, the properties of the light can reveal a galaxy's distance. This distance information comes from the fact that the universe is expanding, which produces a Doppler shift in the spectrum of the galaxy. Combining this effect with Hubble's law, which states galaxies at greater distances appear to be moving away from us at a faster rate, allows astronomers to calculate the galaxy's distance. Using the shape of the spectrum to determine this distance is known as measuring the "photometric redshift."

The process of determining photometric redshifts requires extensive data at different wavelengths. Fortunately, data exist that can be used to calculate these masses and redshifts within the deep Hubble pointings. These data come from multiple telescopes, including additional deep imaging performed with the Subaru Telescope, the two 10-meter Keck Observatory telescopes, and the Hubble Space Telescope.

A distant galaxy merger is seen through a gravitational lens. The lensing galaxy is an edge-on spiral, which appears as a diagonal "line" in the image. Behind it lies the distorted image of a galaxy merger similar in appearance to the closer Antennae Galaxies, but which occurred when the universe was just 7 billion years old. NASA/ESA/ESO/W. M. KECK OBSERVATORY

However, even with our deepest images, we still are not reaching the faintest galaxies at the most distant cosmic times — or at least not all of them. The question then becomes: How many galaxies are we on the cusp of discovering?

Galaxy mass distribution

The answer lies in the distribution of galaxy masses — i.e., how many galaxies there are at a given stellar mass within a volume of space. It turns out that galaxies have a regular distribution — that is, there are not just random numbers of galaxies at different masses. What we know and have known for some time is that many more low-mass galaxies exist than high-mass galaxies.

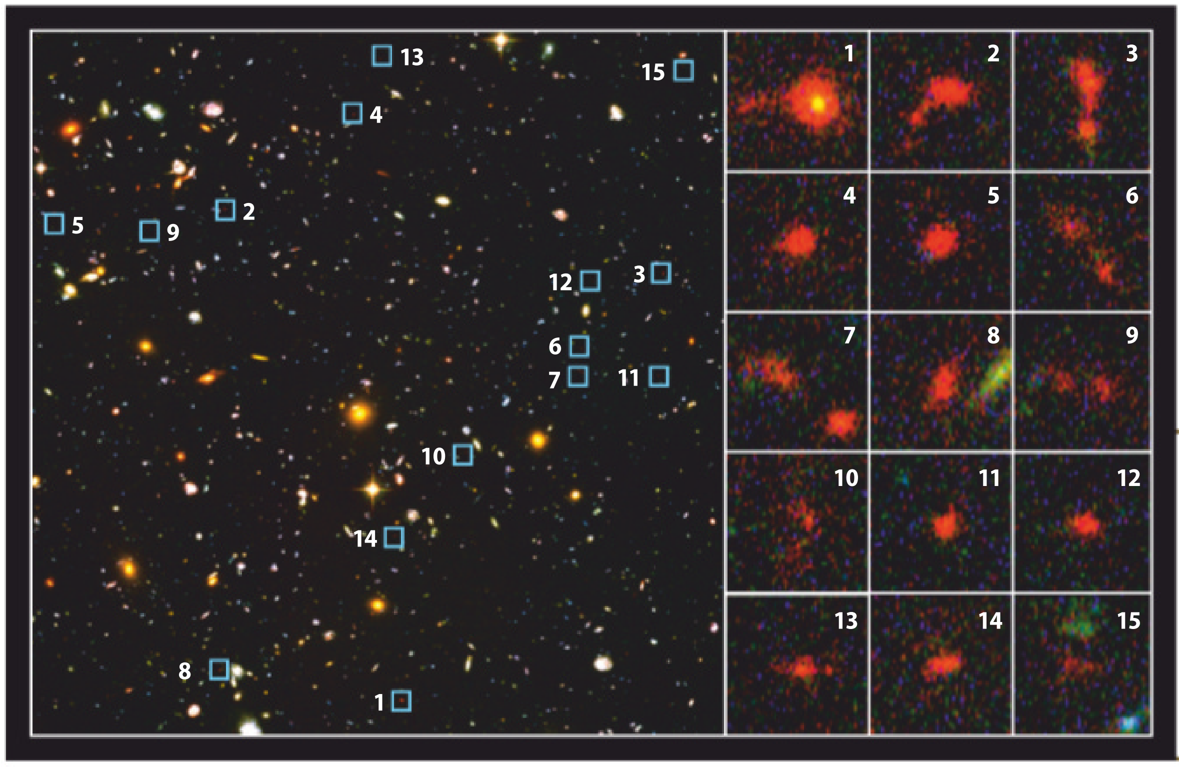
At high masses, the distribution of galaxies is "normal" or Gaussian, but at low masses, the distribution is a power-law. The slope of this power-law describes for the most part how many galaxies exist.

Astronomers want to characterize the distribution of galaxy luminosities and masses over time. They do this with what is called the Schechter function, which combines the power-law and normal distributions we see.

This distribution holds very well throughout the universe — in all environments. In fact, the observed distribution of masses is predicted using computer simulations of galaxy formation based on our current cosmological models.

The amazing thing is that as we look further back in time, at higher and higher redshifts, the slope of the Schechter function becomes steeper and steeper. This means that the further back in time we look, the more low-mass galaxies exist. In other words, the early universe was full of tiny galaxies. Larger galaxies didn't exist in abundance until later cosmic times, after numerous small galaxies merged into bigger ones. In fact, for every one galaxy that exists today, there were approximately 10 times as many galaxies when the universe was just a billion years old.

Moreover, we see that the high number density of galaxies in the early universe declines until it



These tiny, irregular red galaxies, singled out from just a portion of the Hubble Ultra Deep Field, are among the most distant — and youngest — ever seen. Existing at a time when the universe was less than a billion years old, these galaxies merged over time to form the more massive galaxies we see today. NASA, ESA, R. BOUWENS AND G. ILLINGWORTH (UNIVERSITY OF CALIFORNIA, SANTA CRUZ, USA) reaches the number we find today. This can only happen by galaxy destruction. That is, small galaxies merged over time to form not only fewer galaxies, but also galaxies that are much more massive than they were in the early universe.

These are important conclusions. When we count the galaxies throughout the whole history of the universe, we arrive at a total of 2 trillion. This is at least a factor of 10 higher than we previously thought.

It's important to note that this discovery hasn't changed the amount of matter in the universe, only the number of galaxies containing that matter. Because the universe we see now is the result of mergers, the greater number of galaxies in the past doesn't add mass — it simply moves it into a greater number of smaller units than are around today.

The meaning of 2 trillion

These results have a few important implications. First, galaxy evolution must have occurred through mergers. There's no other way the number of galaxies in a given volume of the universe can decline by such an amount.

Second, consider Olbers' Paradox, which addresses why the night sky is dark. The paradox states that if the universe is infinite in time and space, then stars should occupy every point in the night sky, making it light. However, this is not the case, and for at least the last few hundred years, astronomers have been asking why.

These results for the number of galaxies show that there is an alternate interpretation to this problem. Because so many galaxies exist, every point in the sky should be occupied by a galaxy. However, we do not see most of these galaxies because the human eye can only detect light with wavelengths less than about 700 nanometers. The optical light from distant galaxies is not visible at these wavelengths because the Doppler effect shifts this light to wavelengths longer than 700 nm.

Based on this effect, the light that should be visible from such faraway galaxies would have to originate in the ultraviolet portion of the spectrum in order to become lengthened into visible light by the time it reaches Earth. However, such UV wavelengths are easily absorbed by hydrogen within the host galaxy itself, as well as in the intergalactic medium.

This is why astronomers required near-infrared observations to discover these galaxies, and why the WFC3 was the critical instrument for this discovery. In the next year, the James Webb Space Telescope will launch. This successor to Hubble will probe much more deeply than its predecessor, not only examining fainter galaxies at the distances we can now study, but also expanding our knowledge of galaxies to even farther distances as well. This will increase our understanding even more, and undoubtedly refine our knowledge of how many galaxies exist in the universe and the implications of this number for cosmology and galaxy formation.

Astronomers are tasked with piecing together the complete picture of our universe, from its earliest days to the present epoch. Our ability to detect fainter, younger objects is continually increasing. As deeper data emerge, we're able to better fit the observations we make to the models we've developed to describe the universe — a universe, we now know, that contains not billions, but trillions, of galaxies.

Armed with this information, astronomers now have a better understanding of how our current universe evolved, and can more accurately predict where it's headed.

Christopher J. Conselice *is a professor of astrophysics at the University of Nottingham, where he studies galaxy evolution and formation.*

The Antennae Galaxies are a famous pair of spiral galaxies in the middle of a merger that's been going on for the past several hundred million years. When the merger is complete, a single large galaxy will be left in their place. ESA/HUBBLE AND NASA

When we count the galaxies throughout the whole history of the universe, we arrive at a total of 2 trillion. This is at least a factor of 10 higher than we previously thought.

RELATIV

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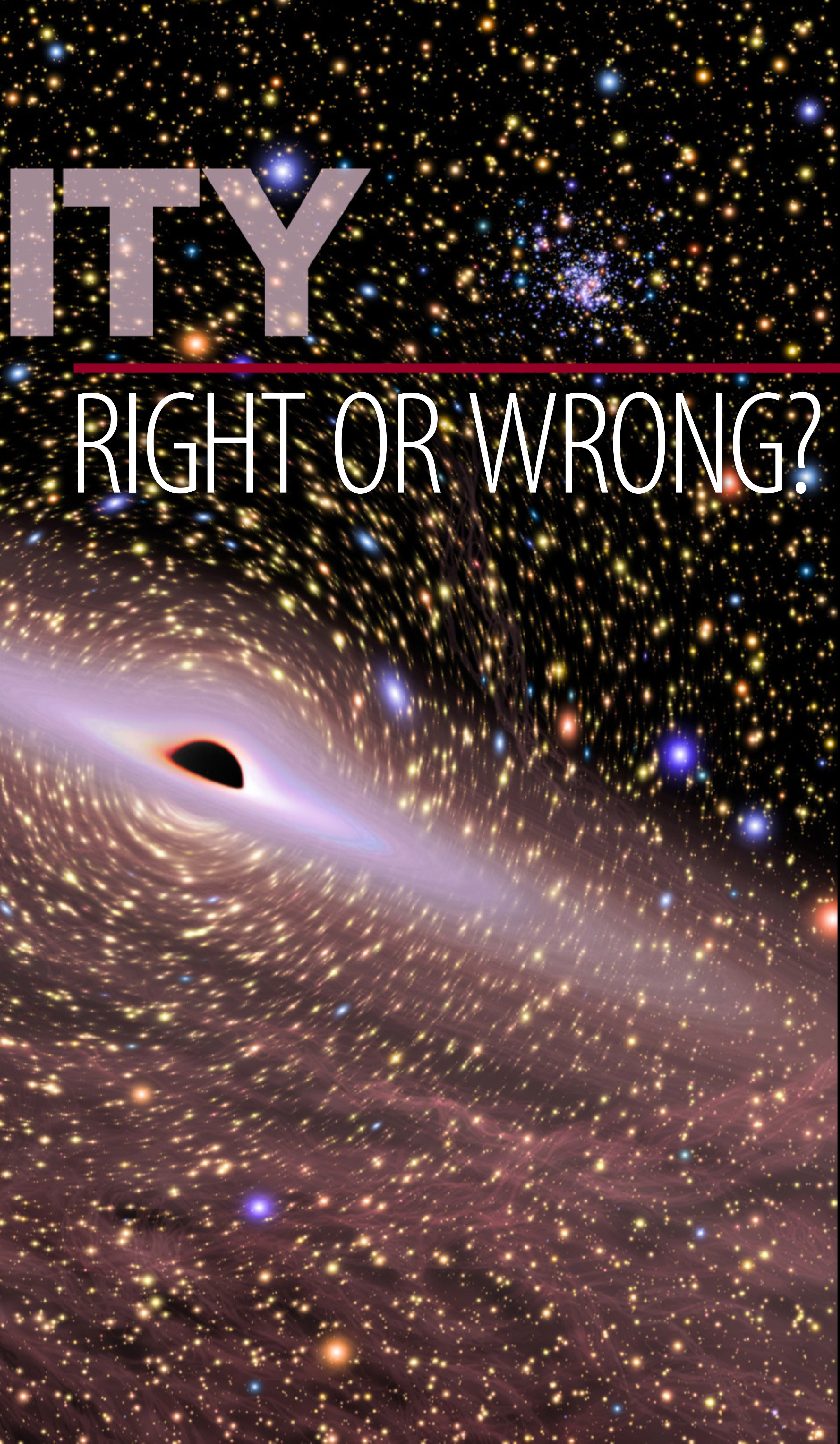
RIGHT OR WRONG?



Einstein's relativity replaced Newton's gravity. Now observations of black holes might test the limits of Albert's masterpiece.

by Jesse Emspak

The event horizon of the supermassive black hole at the center of the Milky Way appears dark against a bright maelstrom of swirling gas and infalling matter. Astronomers hope to probe general relativity's limits by imaging this black hole.

ADOLF SCHALLER FOR *ASTRONOMY*

ON FEBRUARY 11, 2016, two teams of scientists announced the first observation of gravitational waves, a phenomenon that Albert Einstein's general theory of relativity had predicted a century earlier. The Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo collaborations had caught ripples in space-time itself: the wake of two black holes that collided and merged more than a billion light-years away.

It was a triumph for general relativity. But to physicists, it wasn't an end; it was a beginning. Black holes — objects so dense that not even light can escape — proved Einstein right. Now, scientists want to use them to stretch relativity to its limits, and perhaps even break it.

"It's not that we think relativity's wrong," says Andrea Ghez, a professor of physics and astronomy at the University of California, Los Angeles, and director of UCLA's Galactic Center Group. "It's just incomplete."

Astronomers and physicists are working to probe black holes with radio telescopes and gravitational waves, as well as tracking the motions of stars and other matter around black holes to see if they follow the rules laid down by Einstein a century ago.

The general theory of relativity has passed every test physicists have devised so far. It underlies our understanding of space, time, and gravity; Global Positioning System satellites even take it into account. It superseded Isaac Newton's conception of gravity as a force that acts instantaneously at a distance.

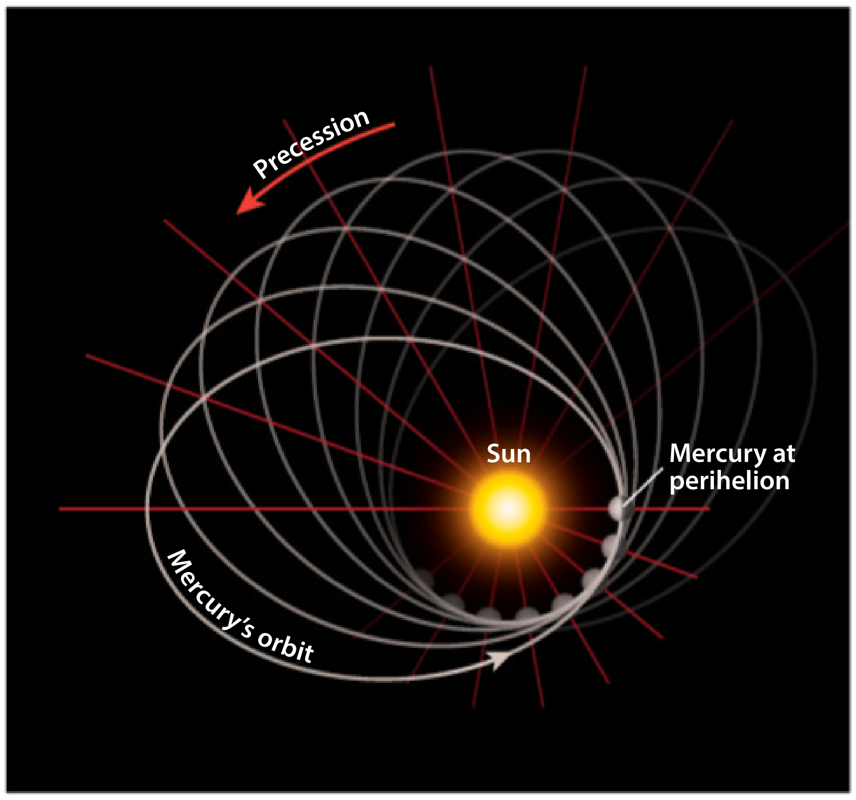
While the math in general relativity is more complex than in Newton's gravity, its basic principles can be stated simply. Relativity treats gravity as a curvature in space-time. (Space-time itself merely adds time as a coordinate to the three normal space coordinates: length, width, and height.) An object bends the fabric of space-time, making a gravitational "well" at the location where a planet, star, black hole — or anything with mass — resides.

Meanwhile, light follows a curved path, bending around the edges of the well. An object with enough mass can behave like a lens, making objects behind it visible. And light traveling out of a gravity well is stretched, becoming redder as it climbs out. Time also slows as gravity gets stronger, so clocks near a black hole, a star, or even Earth's surface will tick more slowly than those farther away.

Is it complete?

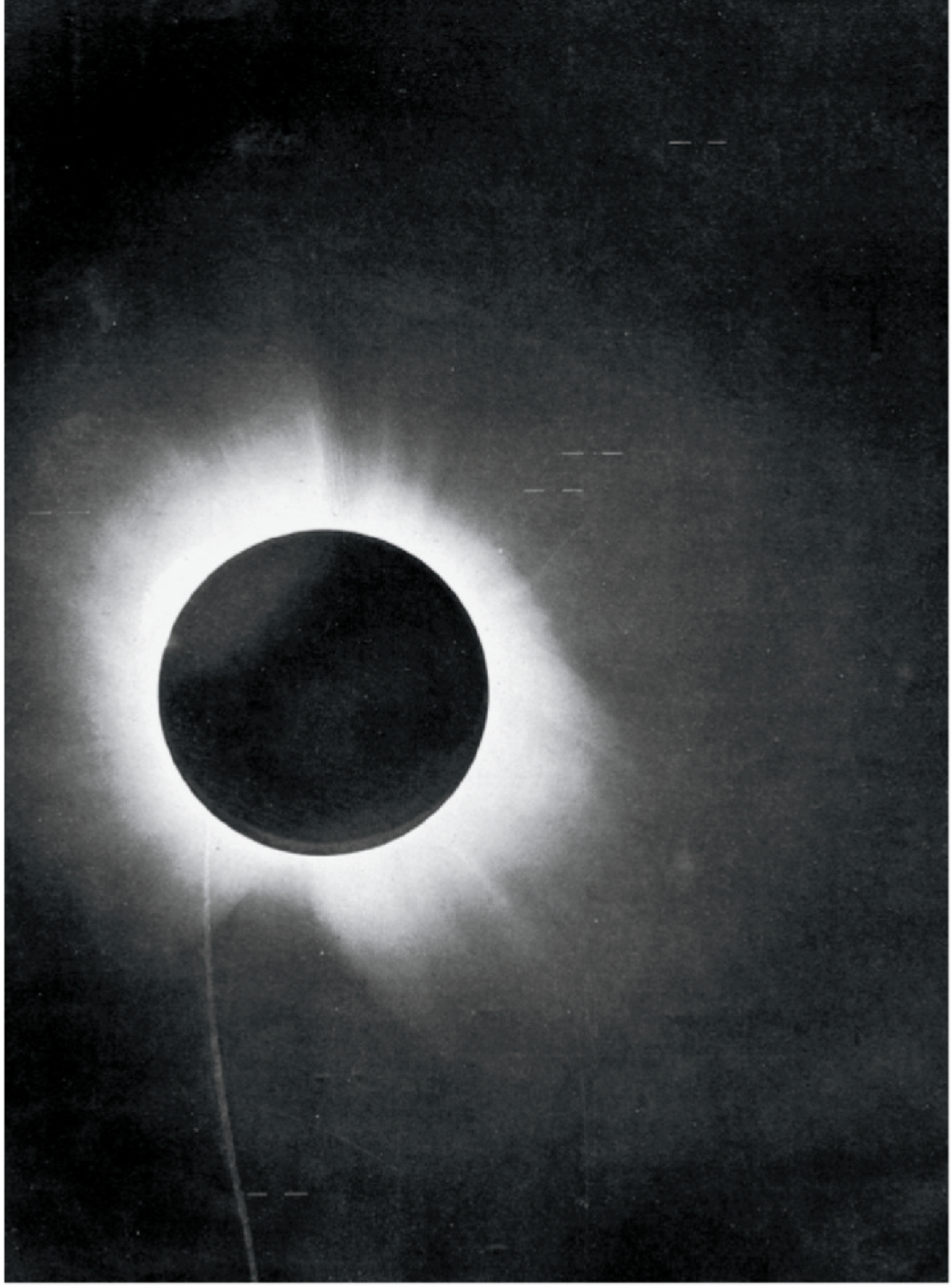
Although relativity has passed every test with flying colors, gaps exist that have driven research for decades. A prime example is that Einstein's gravity does *not* seem to fit into quantum mechanics, even though the three other fundamental forces of nature do. Each of the other three forces is mediated by particles: Photons carry the electromagnetic force, gluons carry the strong nuclear force, and W and Z bosons carry the weak nuclear force. But no one has yet observed the corresponding particle that should carry the gravitational force — the graviton — though current theories say it should exist.

Ghez says that some phenomena don't quite fit into Einstein's paradigm. Universal expansion is one. While it's true that general relativity implies galaxies should be racing apart, the underlying reasons why cosmic expansion seems to



Mercury's shifting perihelion

The perihelion of Mercury, the point in the planet's orbit where it comes closest to the Sun, precesses nearly 2° per century. Newton's laws accounted for all but 43" of this change; general relativity resolved the rest. The advance illustrated here is exaggerated to show detail. *ASTRONOMY*: ROEN KELLY



This photo of the May 1919 solar eclipse shows that the positions of stars (inside the dashed lines) have changed in accordance with general relativity when their light passed near the Sun's limb. F.W. DYSON, A.S. EDDINGTON, AND C. DAVIDSON

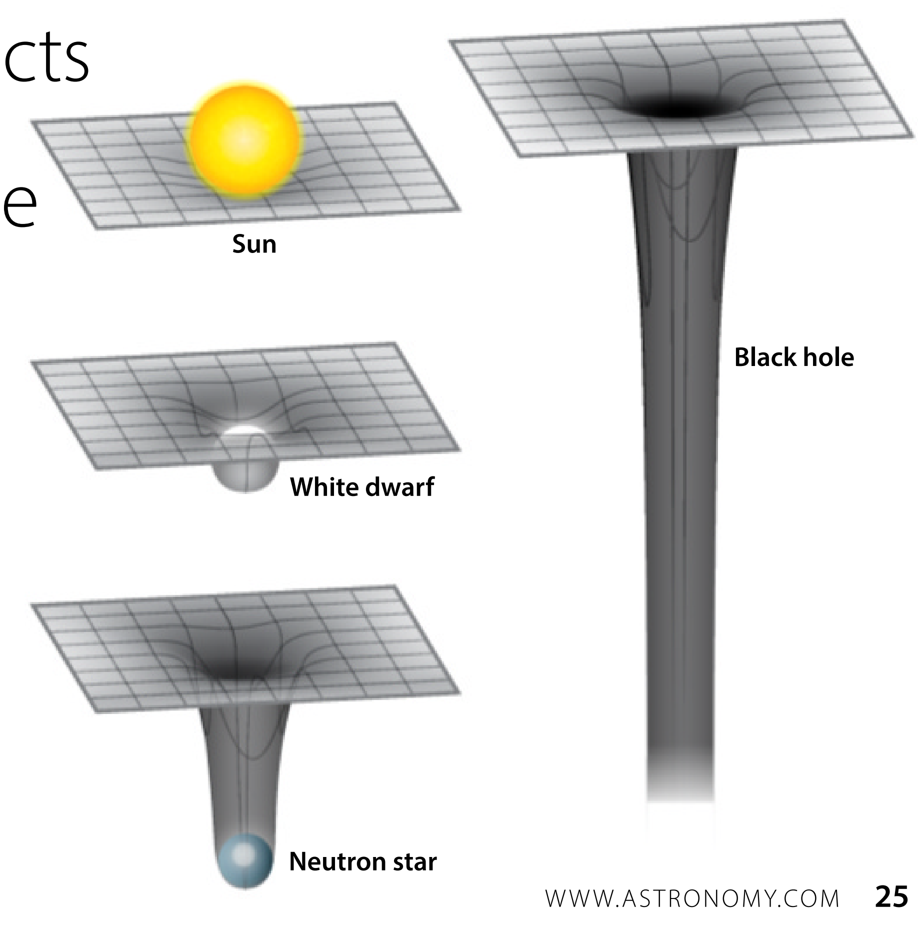
> **"It's not that we think relativity's wrong. It's just incomplete."**
>
> **— Andrea Ghez**

be accelerating are still controversial. "Is that because we don't have the right theory to describe gravity?" she asks. "Observationally, now we are just pushing the edges. We want a more complete version of gravity; there's evidence this version isn't good enough."

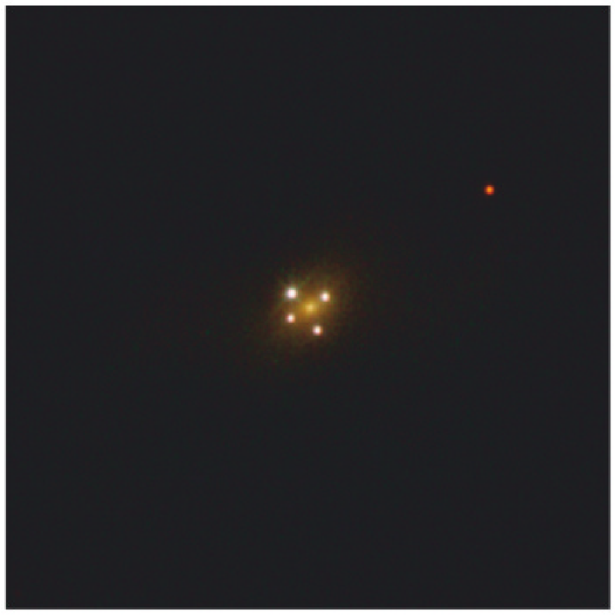
Tim Johannsen of the University of Waterloo in Ontario, studies gravity in extreme environments. He agrees that black holes may offer a way to find relativity's breaking points. "There have been many experimental tests of general relativity, but hardly any of them have probed the strong-field regime in the immediate vicinity of a black hole so far," he says.

The first tests involved the far weaker field surrounding the Sun. For example, the point in Mercury's orbit where it

How objects distort space-time



Any object with mass warps space-time. But objects with more mass and greater density create greater gravity wells. This illustration compares the relative deformations from different objects. Notice that a black hole essentially rips a hole in the fabric of space-time. *ASTRONOMY*: KELLIE JAEGER



ABOVE: The Einstein Cross vividly shows the effects of gravitational lensing. Light from a distant quasar passes through the outskirts of a diffuse galaxy, which acts as a lens to magnify and bend the quasar's light into four distinct images. ESA/HUBBLE AND NASA

RIGHT: Gravitational lensing also occurs on grand scales. Here, the giant galaxy cluster MACS J0717.5+3745 magnifies and distorts light from more distant galaxies, warping their light into arcs and streaks. NASA/ESA/THE HST FRONTIER FIELDS TEAM (STScI)

comes closest to the Sun, called perihelion, advances about 2° per century. Relativity accounts for the tiny fraction, just 43" per century, that Newton's laws cannot. And observations of a total solar eclipse in 1919 found a small bending of light by the Sun's gravitational field. Later, the discoveries of gravitational lensing and gravitational waves helped confirm relativity's power to explain nature. It would seem that Einstein is in good shape, but the nagging question is whether his theory will hold up under more extreme conditions, or eventually show its incompleteness as Newton's theory did.

Yet even with the knowledge that general relativity might not be the last word, any new theory still has to fit all the results that have come before. "The bar is getting higher," says Nicolas Yunes, a physicist at Montana State University. "Whatever theory of gravity you decide to devise, at the very least, it has to predict the same gravitational waves that [LIGO] observed."

Forging a black hole

To make a black hole, you need to compress a lot of mass into a very small

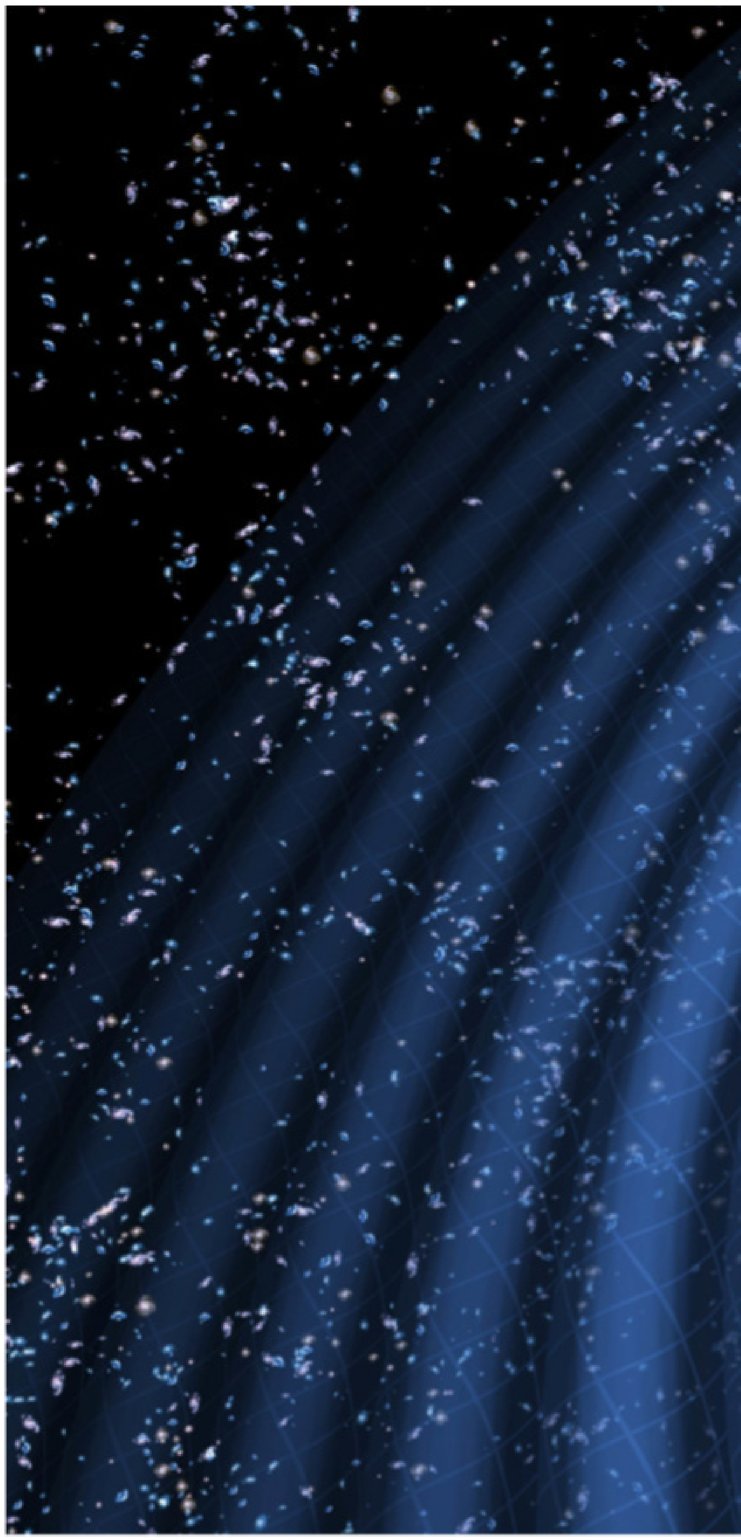
space. Einstein's theory says it doesn't matter what that mass is, but astronomers think nature makes stellar-mass black holes when massive stars die. All stars spend most of their lives fusing hydrogen into helium in their cores. The energy this produces creates an outward pressure that balances the inward pull of gravity. After a star exhausts its core hydrogen, it eventually starts to fuse helium into carbon.

More massive stars can tap into additional fuels. Ultimately, silicon fuses into iron and nickel. But the process stops there because fusing heavier elements consumes, rather than releases, energy. The star can no longer support its own weight with radiation pressure from fusion, so it collapses. The implosion triggers a shock wave that tears the star apart in a violent supernova explosion. For stars that begin life with more than 20 solar masses, the core left behind collapses to infinite density and becomes a singularity. An event horizon forms around the singularity, and you have a black hole.

The event horizon — the point of no return — is surprisingly small. The black hole at the center of the Milky Way Galaxy, known as Sagittarius A* (pronounced A-star), holds about 4 million times the Sun's mass, but its event horizon is only 15 million miles (24 million kilometers) across. It would fit inside Mercury's orbit with plenty of room to spare. A black hole with 10 times the Sun's mass would have an event horizon that spans 37 miles (60 km) and would fit inside Rhode Island. And if Earth were compressed into a black hole, it would be the size of a marble. The event horizon radius increases in direct proportion to the black hole's mass, but unlike Hollywood treatments, black holes don't vacuum matter up. If an Earth-mass black hole replaced our planet, the Moon's orbit wouldn't change.

The small size matters because the gravitational field changes drastically as one approaches the event horizon. That's why black holes are such good arenas for testing relativity. The gravity wells are steep — a person 3 feet (1 meter) from an Earth-mass black hole would feel a force more than 40 trillion times the gravity at Earth's surface. In the vicinity of a black hole, the bending of light is easy to spot, and effects like time dilation and deviations from Newtonian mechanics are large enough to observe readily. If relativity stops working, then near a black hole is where we are likely to see it happen.

> **"How do you convince yourself you know what Newton is predicting?"**
>
> **— Andrea Ghez**



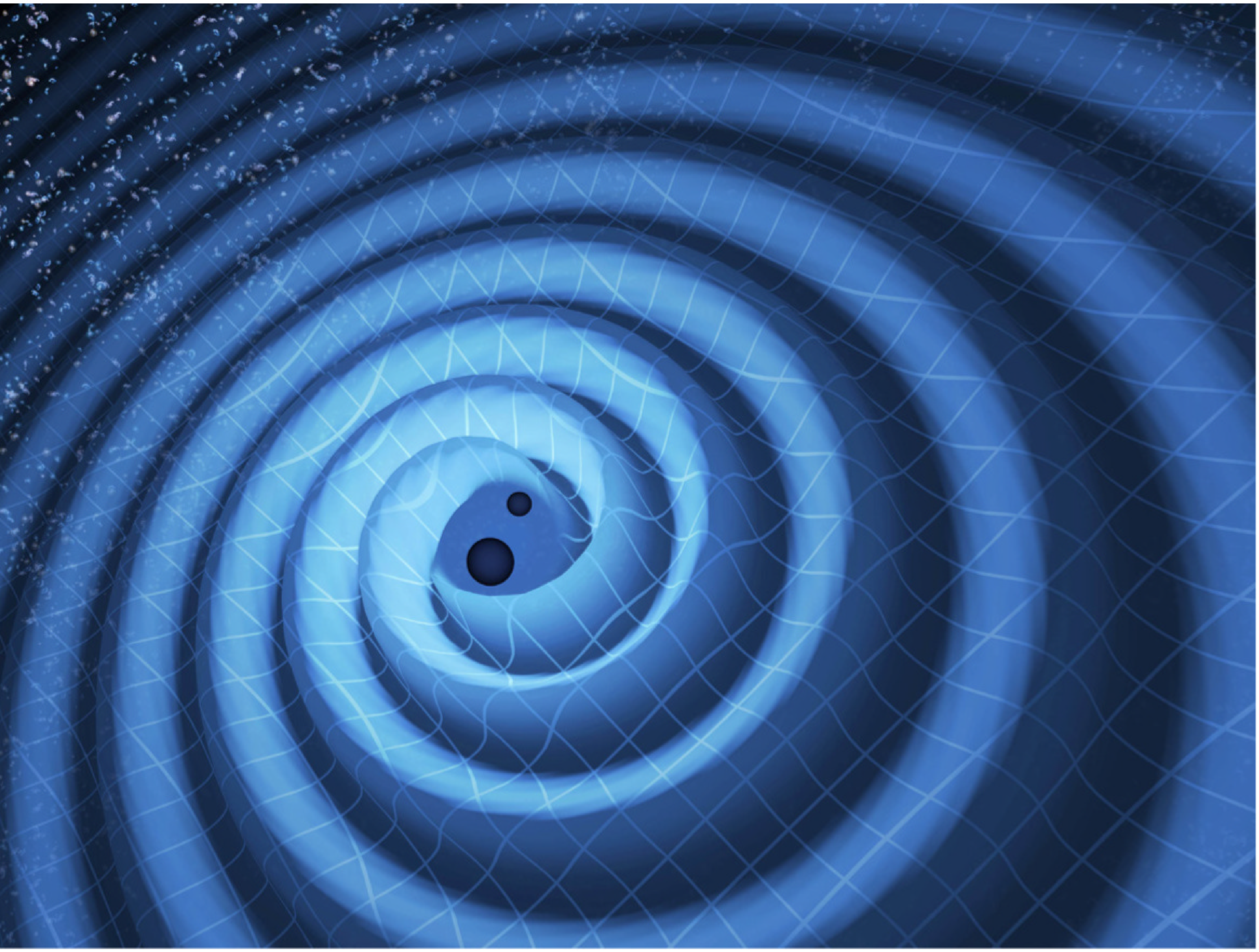
The LIGO and Virgo collaborations have detected gravitational waves from the mergers of several black hole pairs. This illustration depicts the merger seen December 25, 2015, when black holes of 8 and 14 solar masses merged into a single 21-solar-mass object. LIGO/T. PYLE

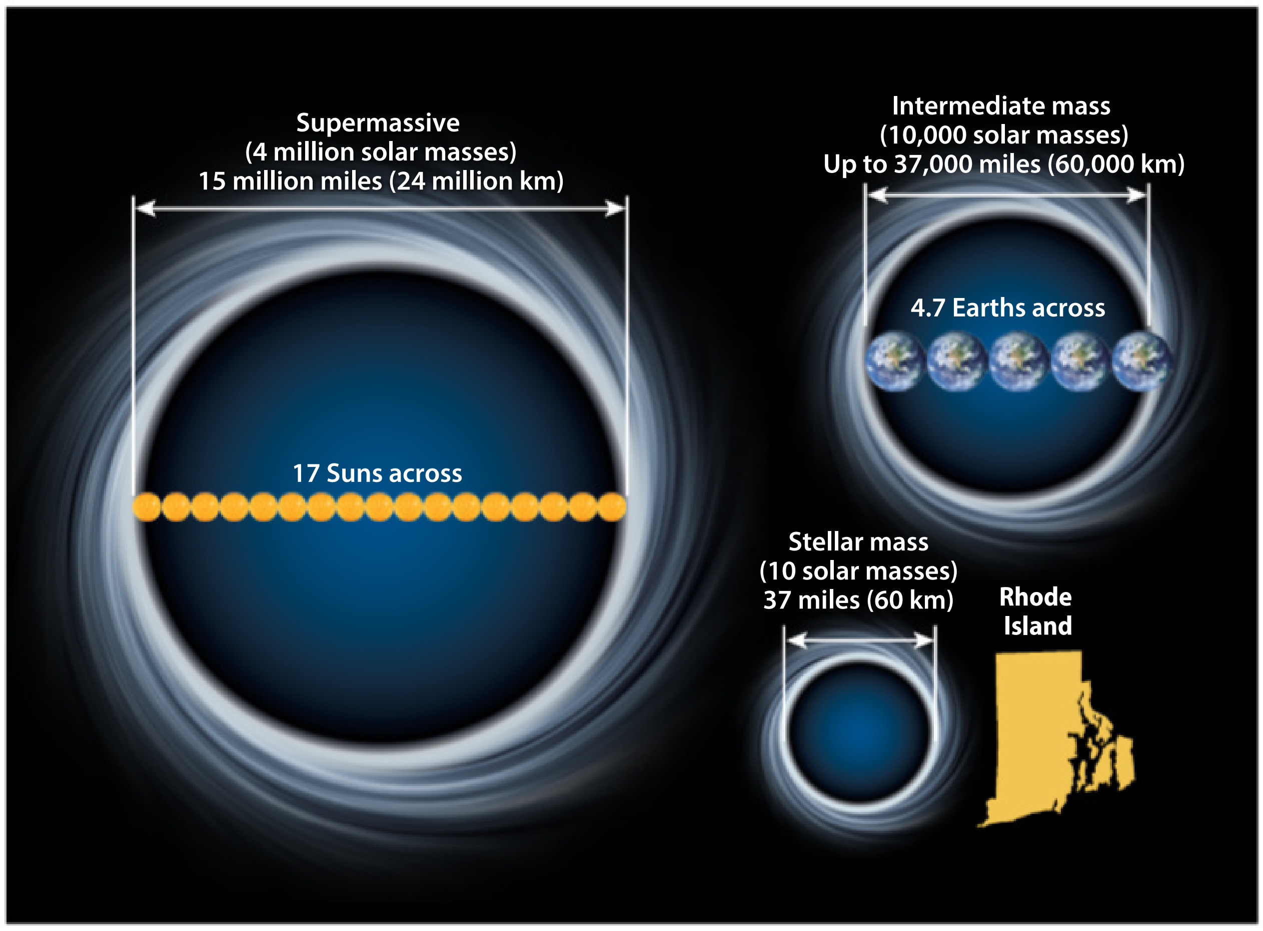
The hurried paths of stars

To track down some of these relativistic effects, Ghez's research team is using a method similar to the one scientists used to analyze Mercury's orbit. Sagittarius A* is the closest supermassive black hole, and astronomers can resolve individual stars orbiting it. One in particular, called S2, takes 16 years to complete its highly elliptical orbit. The black hole's mass is why the star goes so fast. By the time it made its closest approach to Sagittarius A* in mid-2018, at a distance about three times as far from the black hole as Pluto is from the Sun, it was moving at between 1 and 2 percent the speed of light.

After years of observations, data from 2018 will give the researchers enough information to measure deviations from Newton's laws due to general relativity accurately, Ghez says. Paradoxically, the relativistic effects are so large they actually make it more difficult to do a Newton's-law calculation. "How do you convince yourself you know what Newton is predicting?" she says. Thus far, Einstein's theory should show a difference from a Newtonian calculation of about 120 miles per second (200 km/s). Further deviations from that might show that Einstein's theory is starting to fray.

The team's observations also touch on another mystery, says Ghez. Stars near the galactic center should be relatively old. The clouds of gas and dust that




Supermassive
(4 million solar masses)
15 million miles (24 million km)
17 Suns across
Intermediate mass
(10,000 solar masses)
Up to 37,000 miles (60,000 km)
4.7 Earths across
Stellar mass
(10 solar masses)
37 miles (60 km)
Rhode
Island

The sizes of black holes

The diameter of a black hole's event horizon increases in direct proportion to its mass. A black hole with 10 times the Sun's mass would span 37 miles (60 km), while the one in the Milky Way's center measures 17 Suns across.

ASTRONOMY: ROEN KELLY

One of LIGO's twin detectors (above) is in Livingston, Louisiana, some 25 miles (40 km) east of Baton Rouge. The other detector is in Hanford, Washington.

CALTECH/MIT/LIGO LAB

would give birth to stars shouldn't be stable so close to a supermassive black hole; calculations based on relativity show that tidal forces should disrupt them. Yet stars near the center skew young. Unless someone can invoke a mechanism for quickly getting these youngsters in from an outer region, they demonstrate that scientists must be missing something.

In the shadows

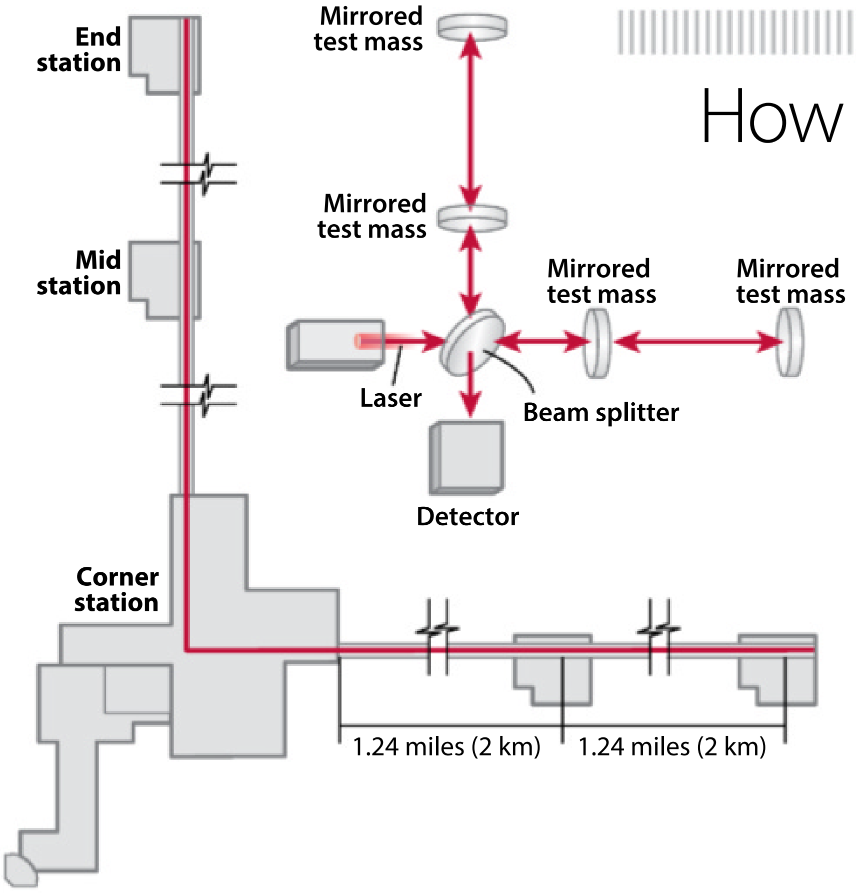
Johannsen is among the astronomers taking a different tack, using the Event Horizon Telescope (EHT) to see if relativity breaks down in the "shadow" of a black hole.

The EHT is a collection of radio telescopes spread around the world. Using a technique called very long baseline interferometry, the telescopes work together to achieve a resolution comparable to a single instrument with a diameter nearly as wide as our planet. The array delivers enough resolution for radio astronomers to observe the edges of Sagittarius A*, as well as the much larger supermassive black hole that lurks at the center of the giant elliptical galaxy M87 in the Virgo Cluster. Accretion disks of gas and dust surround both black holes. Such disks tend to form around black holes because their strong tidal forces rip apart any object that gets too close. Friction within the disk heats the material to millions of degrees before it falls into the hole, and the gas glows brightly in wavelengths ranging from X-rays to radio.

Since black holes act like lenses, Johannsen's team expects to see a perfect ring of light as the photons from behind the black hole are bent around it. (Although most researchers describe the dark void at the center of the ring as a "shadow," it is really a silhouette of the black hole against the bright background light.) If that ring isn't a perfect circle and shows some oscillations, then a quantum effect may be happening. It would be the first time anyone has seen anything like it around a black hole.

"The shape of a given shadow is almost entirely determined by gravity alone and not by the particulars of the gas and dust that are swirling around the black hole," says Johannsen. "Therefore, the detection of the shadow can potentially be a clean

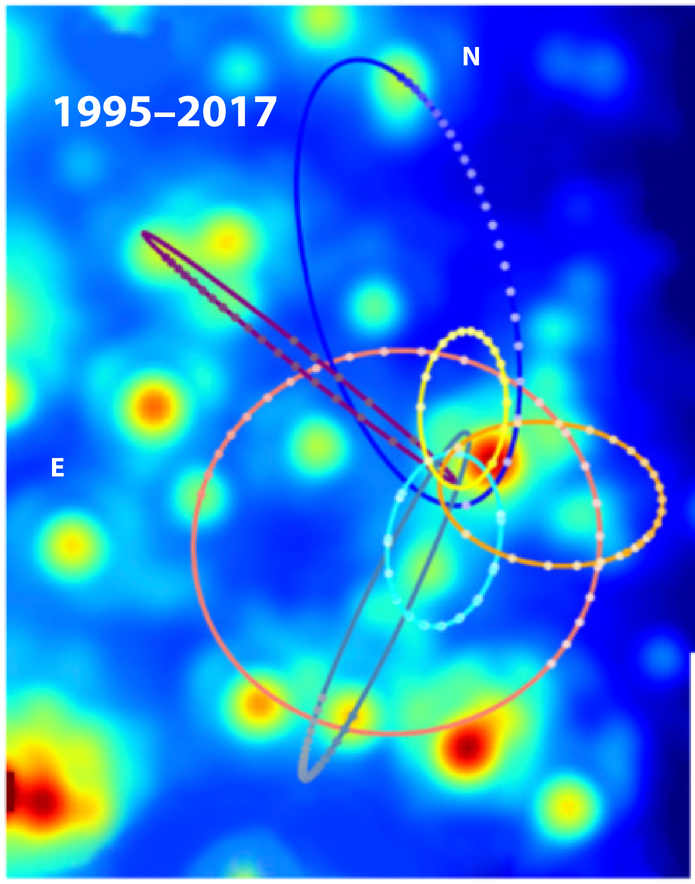
How LIGO works



Each LIGO detector sends laser pulses down two 2.5-mile-long (4 km) arms and then combines the light beams to create an interference pattern. Analyzing these patterns lets scientists measure tiny changes in the distance the light travels in response to a passing gravitational wave.

ASTRONOMY: ROEN KELLY

The 1.9-mile-long (3 km) arms of the Virgo interferometer are nestled in the countryside near Pisa, Italy. This instrument works in tandem with the twin LIGO interferometers in the U.S. THE VIRGO COLLABORATION



Researchers using the 10-meter Keck Telescope have tracked the motions of a handful of stars in orbit around Sagittarius A*. They expect these observations will soon allow them to detect deviations from Newton's laws. KECK/UCLA GALACTIC CENTER GROUP

measurement of the underlying theory of gravity without many of the complications that come with those messy surroundings."

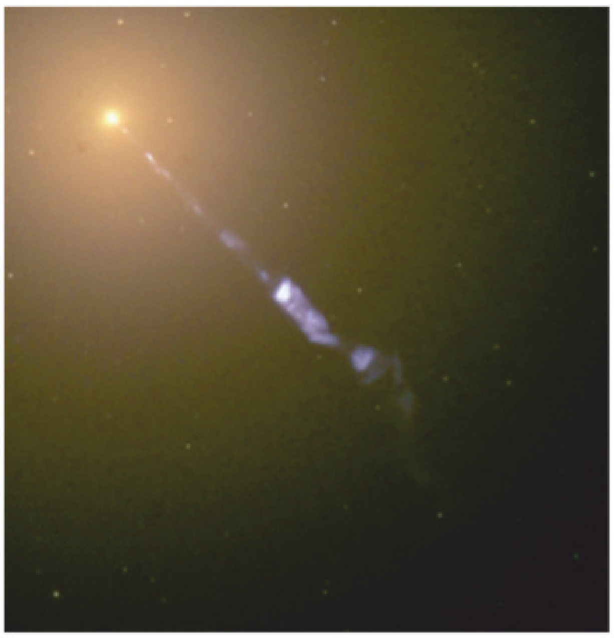
General relativity says the shape of the shadow should be nearly circular with a fixed size. Other theories of gravity posit other shapes. "If we find any of those deviations, there are two possibilities: Either [general relativity] is not correct in the strong-field regime, or [general relativity] still holds but the object is not a black hole but some exotica. Either one would be quite a sensation."

Riding the waves

Perhaps one of general relativity's most famous predictions was gravitational waves. (While Einstein's theory gave gravitational waves a sound mathematical basis, the concept was not unique to him: Henri Poincaré and Oliver Heaviside also floated the concept.) Einstein predicted that accelerating massive objects would cause space-time to ripple. The resulting waves would propagate at the speed of light and not at an infinite speed as Newton's formulation of gravity predicted. As of September 2019, astronomers with the LIGO and Virgo collaborations have picked up unequivocal evidence for gravitational waves about two dozen times.

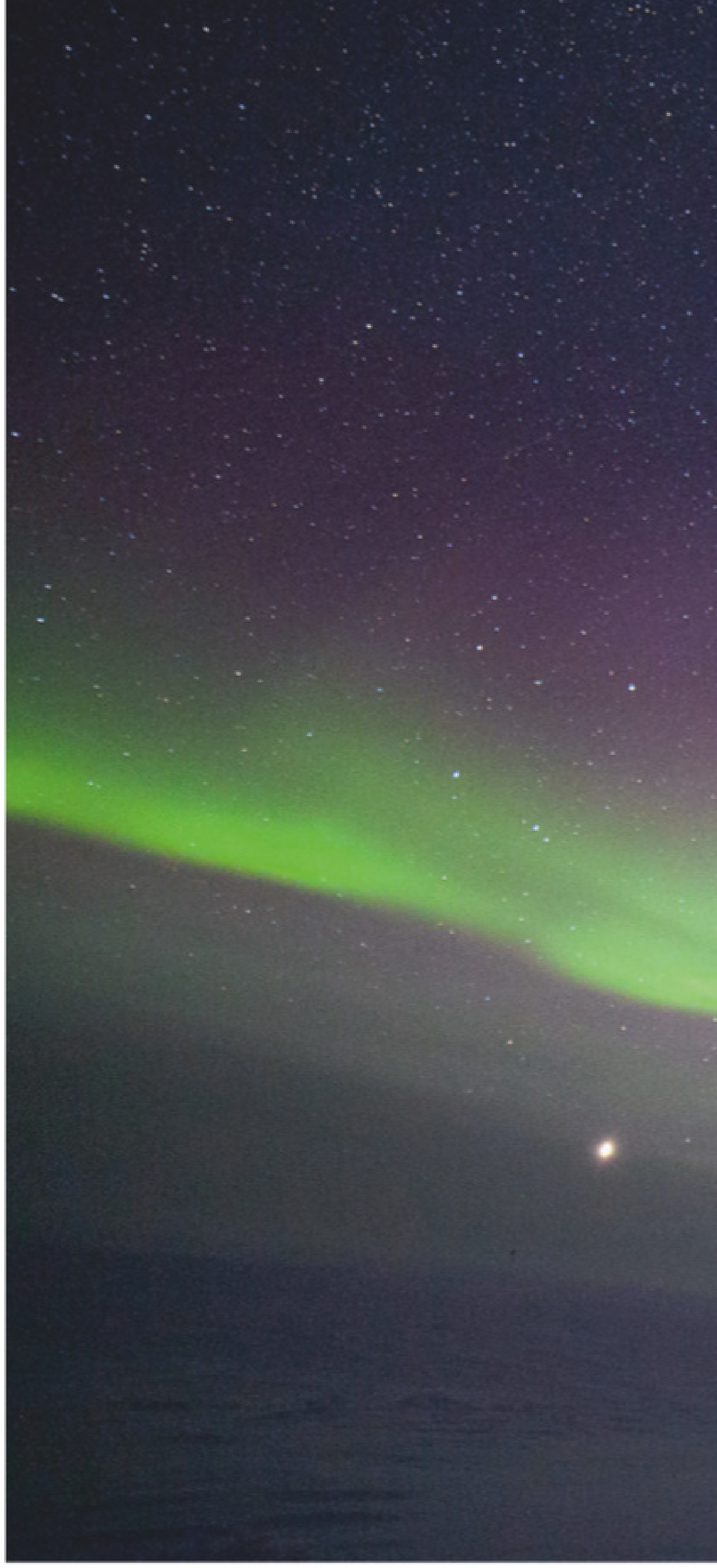
LIGO and Virgo are interferometers. A laser is fired at a beam splitter that sends the light down two perpendicular arms. Each of LIGO's arms is 2.5 miles (4 km) long, while each Virgo arm extends 1.9 miles (3 km). The two beams bounce off mirrors at the end of the arms and return to the beam splitter, where they combine into a single beam before heading into a photodetector. If the two beams travel precisely the same distance before merging, they will either cancel each other out or reinforce each other, and the photodetector will either pick up nothing, or it will see light as bright as the original beam.

Thousands of stars crowd the core of our galaxy, which harbors a 4-million-solar-mass black hole called Sagittarius A*. This near-infrared image reveals many of those stars, some interstellar dust, and the faint glow surrounding the black hole. ESO



> **“The puzzle is getting completed one piece at a time.”**
>
> **— Nicolas Yunes**

LEFT: The supermassive black hole at the center of M87 emits a high-powered jet of subatomic particles. Although this elliptical galaxy lies more than 50 million light-years from Earth, astronomers managed to image its black hole in 2018, using the Event Horizon Telescope.
NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



RIGHT: The Milky Way and aurora australis shine down on the South Pole Telescope, one of about a dozen instruments that form the Event Horizon Telescope. This virtual Earth-sized observatory has imaged a black hole’s event horizon.
DANIEL MICHALIK/SOUTH POLE TELESCOPE

LIGO’s two detectors and Virgo’s one are designed so the photodetectors record nothing if the arms stay the same length. But if the beams travel a different distance — as one would expect if passing gravitational waves distorted spacetime — then the photodetectors will record an interference pattern, and the merged beam will appear brighter or dimmer than the original one. The interferometers can detect changes in the lengths of their arms as small as 1⁄10,000 the width of a proton.

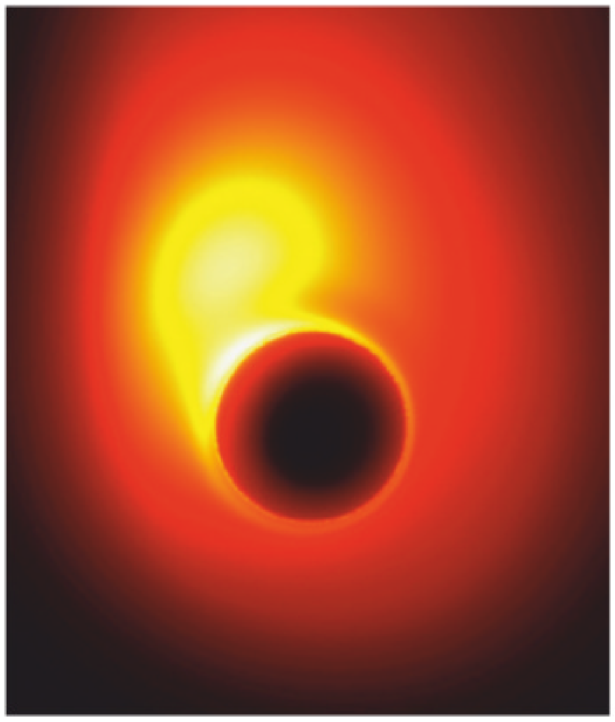
The detection of gravitational waves doesn’t mean Einstein’s theory can rest, however. In many ways, their detection raises as many questions as it answers. A few theorists have started to poke at the observations to see if they reveal hints at a quantum theory of gravity, or at least some connections that don’t violate quantum mechanics.

In late 2016, for example, researcher Jahed Abedi of the Sharif University of Technology in Tehran, along with Hannah Dykaar and Niayesh Afshordi of the University of Waterloo, proposed that “echoes” in the gravitational wave signal might indicate there were some tiny structures near the event horizons of the merging objects, pointing to physics beyond general relativity. The idea wasn’t met with a lot of enthusiasm from fellow scientists. In a set of back-and-forth papers, skeptics stated that they had reservations about the theoretical basis. The next question is whether these echoes will show up in future observations.

A weighty particle

Gravitational waves also may reveal physics beyond relativity in other ways, notes Kent Yagi, a theoretical astrophysicist at the University of Virginia. One way is simply by constraining parameters like the mass of the graviton. If this particle has no mass, then gravitational waves should move at the speed of light, he says. A graviton with mass means that gravitational waves can’t, by definition, go that fast.

If the graviton has mass, it has to be quite small. “We can constrain it to no more than 10^{-20} eV [electron volt] with the first detection, but beyond that, we don’t know. Maybe it’s 10^{-23} eV,” says Yunes. (An electron volt is a common measure of energy in particle physics; scientists often use it as a unit of mass by dividing a particle’s energy by the speed of light squared, per Einstein’s famous



This computer-generated model shows the “shadow” of the 4 million-solar-mass black hole at the Milky Way’s center. Astronomers hope to compare such models with images of the black hole made with the Event Horizon Telescope, to look for any deviations from general relativity.
AVERY BRODERICK (UNIVERSITY OF WATERLOO/PERIMETER INSTITUTE)

equation, $E=mc^2$.) But at a certain point, if there's no mass detected, one has to wonder if it's massless — or even exists.

Meanwhile, other scientists have taken a crack at looking for quantum effects at large scales using combinations of black holes and neutron stars. Neutron stars are the corpses of stars born with more than about eight times the Sun's mass, but less than the 20 solar masses needed to make black holes. They have powerful magnetic fields, and some send focused beams of radio waves in our direction at regular intervals like a lighthouse beacon — pulsars.

John Estes of Long Island University and his colleagues have proposed using the precisely timed signals from a pulsar orbiting a black hole to probe the region near the event horizon. Since black holes bend light, the pulsar's signal would be delayed by a discrete amount when the pulsar passes behind the black hole. If quantum effects are important, then that delay would change in ways general relativity cannot predict, and might even reveal something about how quantum mechanics works with relativity.

But there's another reason to do these kinds of tests. It is far from clear that gravity — and thus general relativity — applies the same way at different scales. Leo Stein of Caltech notes that the physics one encounters near a supermassive black hole, like the one at the center of the Milky Way, might be different from the physics near a stellar-mass black hole.

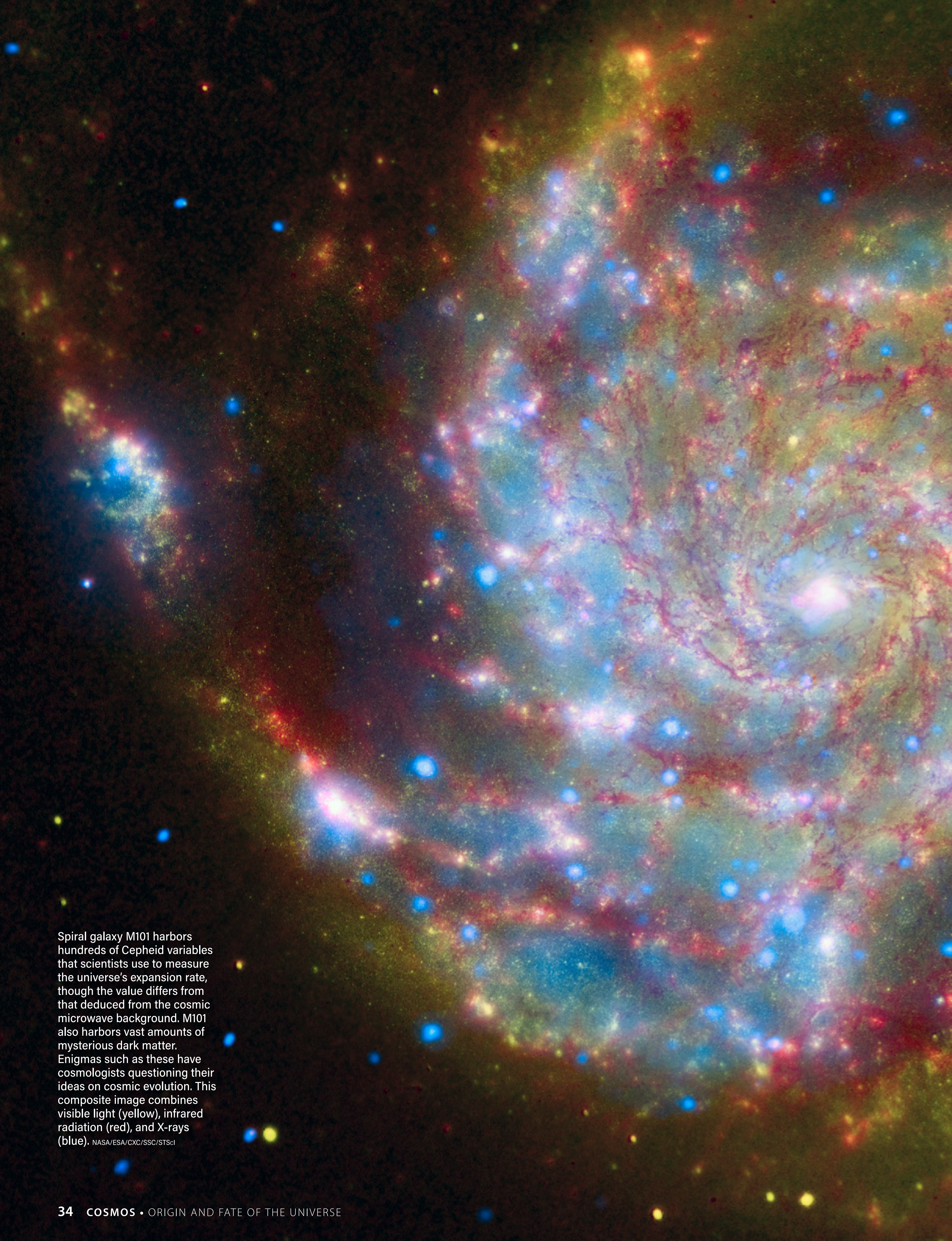
LIGO, for example, showed us that gravitational waves are generated in the expected way near a stellar-mass black hole. The steepness of the curvature of space just outside the event horizon is smaller for larger black holes, however.

"It's potentially very different physics," Stein says. "When curvatures are large, you need to use LIGO. When interested in physics on the millions-of-kilometers scale, there are things you might be able to test with the EHT. In the middle is stuff we have got nailed down, at the solar system scale.

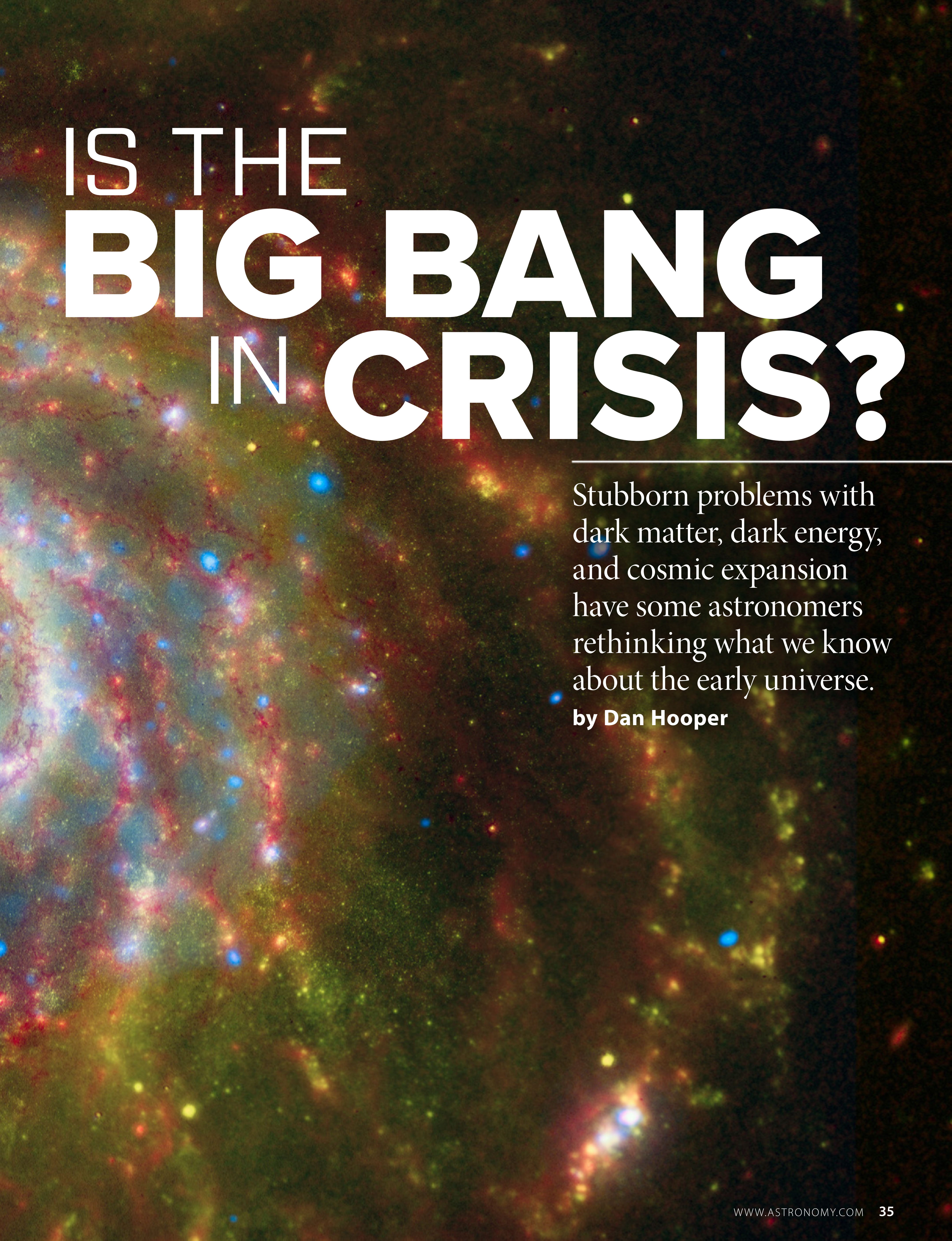
"Cosmologists are interested in changing the theory of gravity at very large distance scales," he says. "String theorists and high-energy physicists are changing the theory of gravity at the quantum level."

As with many mysteries, however, we may have to wait for observations to tell us one way or the other which theory is correct. "The puzzle is getting completed one piece at a time," says Yunes.

Jesse Emspak *is a science writer who lives and works in New York City.*



Spiral galaxy M101 harbors hundreds of Cepheid variables that scientists use to measure the universe's expansion rate, though the value differs from that deduced from the cosmic microwave background. M101 also harbors vast amounts of mysterious dark matter. Enigmas such as these have cosmologists questioning their ideas on cosmic evolution. This composite image combines visible light (yellow), infrared radiation (red), and X-rays (blue). NASA/ESA/CXC/SSC/STScI



IS THE BIG BANG IN CRISIS?

Stubborn problems with dark matter, dark energy, and cosmic expansion have some astronomers rethinking what we know about the early universe.

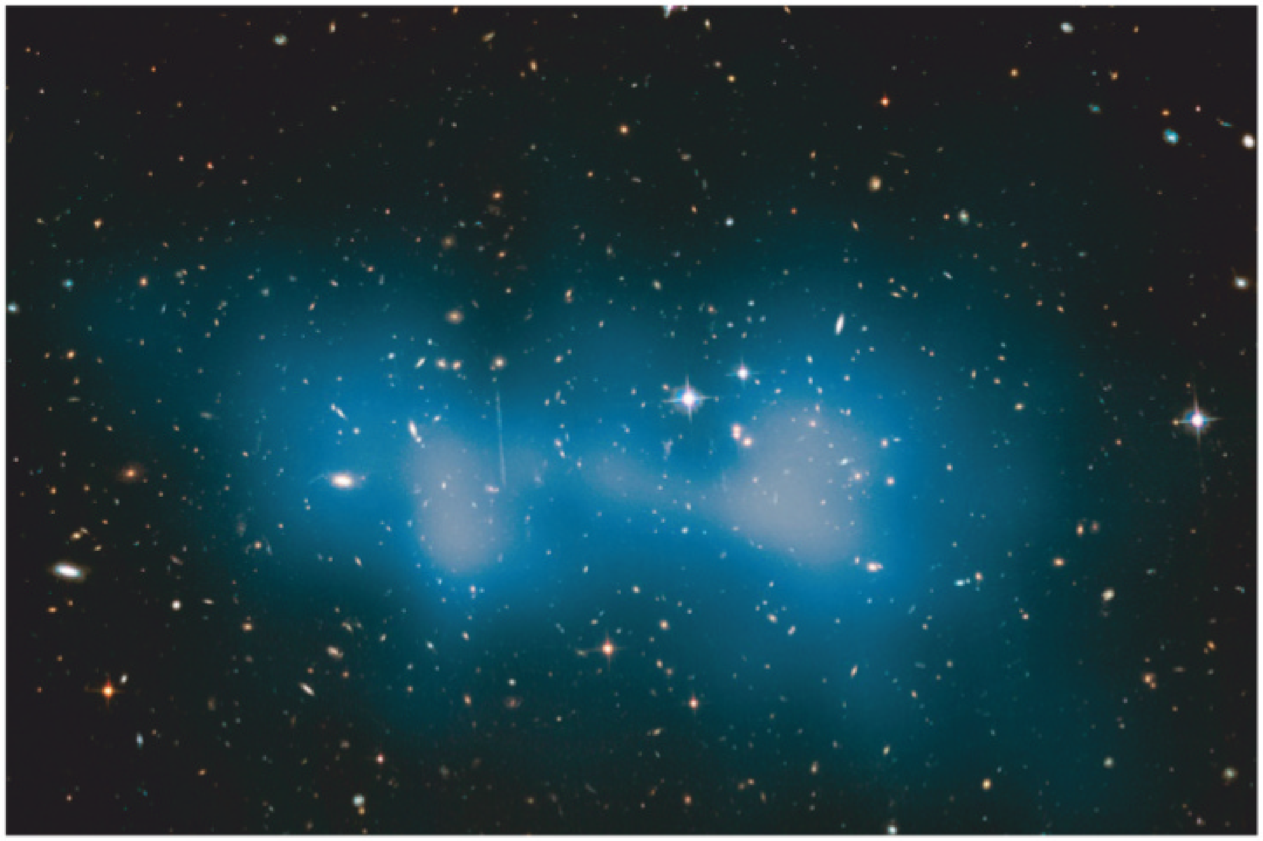
by Dan Hooper

With a diameter 2.5 times that of the Milky Way and containing 10 times as many stars, UGC 2885 ranks among the largest spiral galaxies in the local universe. But there's more here than meets the eye: Invisible dark matter accounts for some 85 percent of UGC 2885's mass. Vera Rubin discovered dark matter in this galaxy during her pioneering study of this mysterious material.
NASA/ESA/B. HOLWERDA (UNIVERSITY OF LOUISVILLE)

A series of powerful observations has made it clear that our universe has expanded for billions of years, emerging from the hot, dense state we call the Big Bang. Over the past several decades, new types of precise measurements have allowed scientists to scrutinize and refine this account, letting them reconstruct the history of our universe in ever greater detail. When we compare the results from different kinds of measurements — the expansion rate of the universe, the temperature patterns in the light released when the first atoms formed, the abundances of various chemical elements, and the distribution of galaxies and other large-scale structures — we find stunning agreement. Each of these lines of evidence supports the conclusion that our universe expanded and evolved in just the way that the Big Bang theory predicts. From this perspective, our universe appears to be remarkably comprehensible.

But cosmologists have struggled — if not outright failed — to understand essential facets of the universe. We know almost nothing about dark matter and dark energy, which together make up more than 95 percent of the total energy in existence today. We don't understand how the universe's protons, electrons, and neutrons could have survived the aftereffects of the Big Bang. In fact, everything we know about the laws of physics tells us that these particles should have been destroyed by antimatter long ago. And in order to make sense of the universe as we observe it, cosmologists have been forced to conclude that space, during its earliest moments, must have undergone a brief and spectacular period of hyperfast expansion — an event known as cosmic inflation. Yet we know next to nothing about this key era of cosmic history.

It's possible that these puzzles are little more than loose ends, each of which will be resolved as cosmologists continue to



TOP: This galaxy cluster, nicknamed El Gordo (Spanish for "The Fat One"), ranks as the largest known cluster in the distant universe. Composed of two individual clusters colliding at more than 1 million mph (1.6 million km/h), this structure holds a mass equivalent to 3 quadrillion Suns. ESA/HUBBLE & NASA/RELICS

ABOVE: The blue color added to this image maps the distribution of dark matter in the El Gordo galaxy cluster. Astronomers traced the presence of this shadowy substance by looking at how it distorts the appearance of more distant objects. NASA/ESA/J. JEE (UNIVERSITY OF CALIFORNIA, RIVERSIDE)

investigate our universe. But so far, these problems have proven to be remarkably stubborn and persistent. With the goal of identifying the individual particles that make up dark matter, scientists have designed and built a series of impressive experiments — yet no such particles have appeared. Even powerful particle accelerators like the Large Hadron Collider have revealed nothing that moves us closer to resolving any of these cosmic mysteries. And despite having measured the expansion history and large-scale structure of the universe in ever increasing detail, we have not gained any substantively greater understanding of the nature of dark energy, the force that seems to be accelerating the expansion of the cosmos.

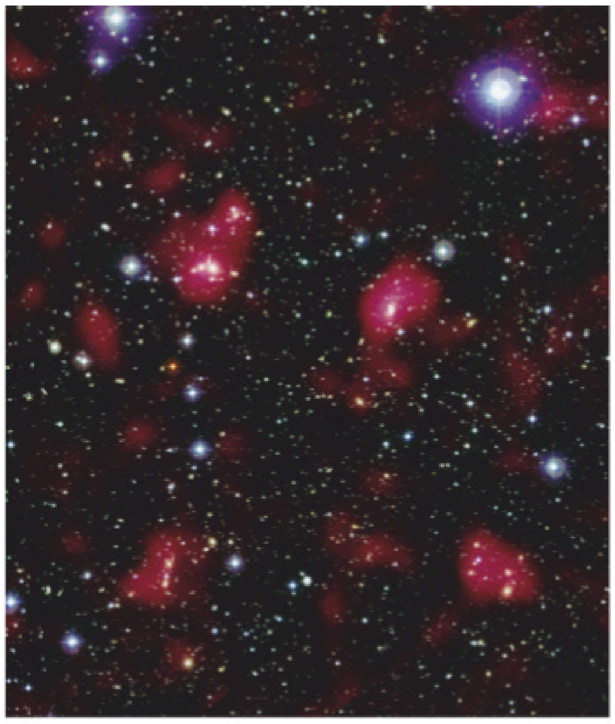
It is from this perspective that some cosmologists have found themselves asking whether these cosmic mysteries might be symptoms of something more significant than a few loose threads. Perhaps these puzzles are not as unrelated as they might seem, but are instead collectively pointing us toward a very different picture of our universe and its earliest moments.

What we've learned by *not* discovering dark matter

Dark matter is likely the most celebrated problem facing modern cosmologists. Astronomers have determined that most of the matter in our universe does not consist of atoms or any other known substances, but of something else — something that does not appreciably radiate, reflect, or absorb light.

Despite not knowing much about the nature of dark matter, cosmologists often

The Coma Cluster packs thousands of galaxies into a sphere measuring more than 20 million light-years across. Fritz Zwicky discovered dark matter in this cluster in the 1930s when he deduced that the galaxies are moving too fast to stay together unless the cluster contains nearly 10 times as much matter as what can be seen. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



The supercluster Abell 901/902 holds hundreds of galaxies and massive amounts of dark matter. The magenta-tinted clumps show the dark matter's distribution, derived from Hubble Space Telescope observations, overlaid on a ground-based image of the supercluster. HUBBLE DATA: NASA/ESA/C. HEYMANS (UNIVERSITY OF BRITISH COLUMBIA) ET AL./THE STAGES COLLABORATION. GROUND-BASED IMAGE: ESO/C. WOLF (OXFORD UNIVERSITY) ET AL./THE COMBO-17 COLLABORATION

speculate about the kinds of particles that might make up this substance. In particular, researchers have long recognized that if dark matter particles interact through a force that is approximately as powerful as the weak nuclear force (which governs radioactive decay), then the number of these particles that should have emerged from the Big Bang would roughly match the measured abundance of dark matter found in the universe today. With this in mind, weakly interacting massive particles — WIMPs — became the best guess for dark matter's nature.

One initially appealing aspect of WIMPs was that scientists thought they knew how to detect the particles and study their properties. Motivated by this goal, physicists engaged in an ambitious experimental program to identify these WIMPs and learn how they were forged in the Big Bang. Over the past couple of decades, researchers have deployed a succession of increasingly sensitive dark matter detectors in deep-underground laboratories that are capable of detecting individual collisions between a dark matter particle and the atoms that make up the target.

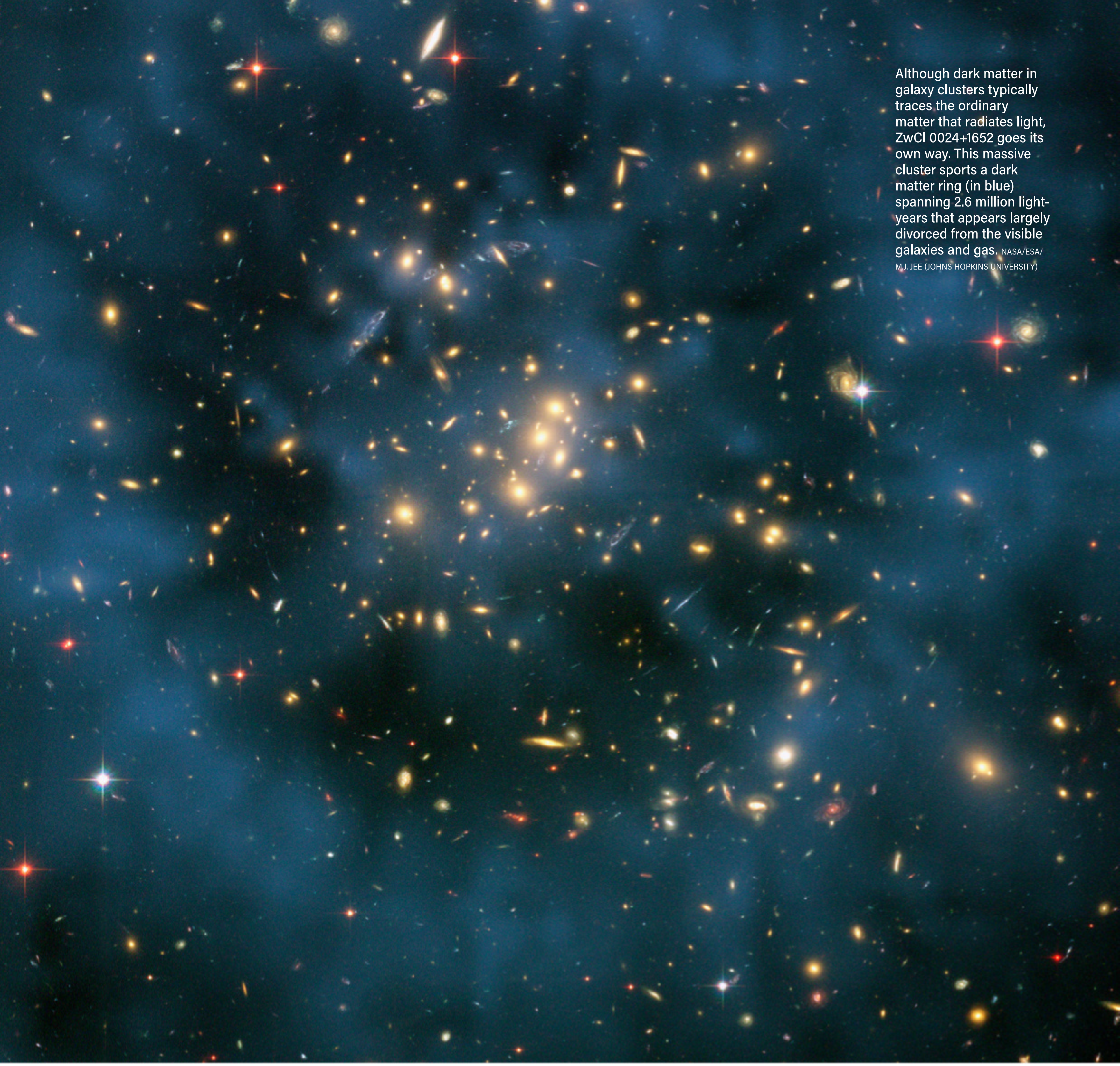
These sophisticated experiments performed beautifully — as well as or better than designed. Yet no such collisions have been observed. A decade ago, many scientists were optimistic that these experiments would bear fruit. But dark matter has turned out to be very different, and far more elusive, than we had once imagined.

Although it's still possible that dark matter could consist of some form of difficult-to-detect WIMPs, the lack of any signal from underground experiments has led many physicists to shift their focus toward other dark matter candidates. One such contender is a hypothetical ultralight particle known as an axion. Axions are predicted according to a theory proposed by particle physicists Roberto Peccei and Helen Quinn in 1977. Although scientists are searching for axions in experiments that use powerful magnetic fields to convert them into photons, these investigations have yet to place very strict constraints on the properties of these particles.

The blue light in this image of MACS J0416.1–2403 shows the arrangement of dark matter in this galaxy cluster. Despite the ubiquity of dark matter in the universe, astronomers still have no good idea what it is made of. NASA/ESA/D. HARVEY (ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE)/R. MASSEY (DURHAM UNIVERSITY)/HST FRONTIER FIELDS

Another possibility that could explain why dark matter has been so difficult to detect is that the first moments of the universe may have played out much differently than cosmologists have long imagined. Take the case of the conventional WIMP. Calculations show that the fledgling universe should have produced vast quantities of these particles during the first millionth of a second or so after the Big Bang, when they reached a state of equilibrium with the surrounding plasma of quarks, gluons, and other subatomic particles. The number of WIMPs that could have survived these conditions — and ultimately contributed to the dark matter found throughout today's universe — depends on how, and how often, they interacted. But when carrying out calculations such as these, scientists generally assume that space expanded steadily during the first fraction of a second, without any unexpected events or transitions. It is entirely plausible that this simply was not the case.

Although cosmologists know a great deal about how our universe expanded



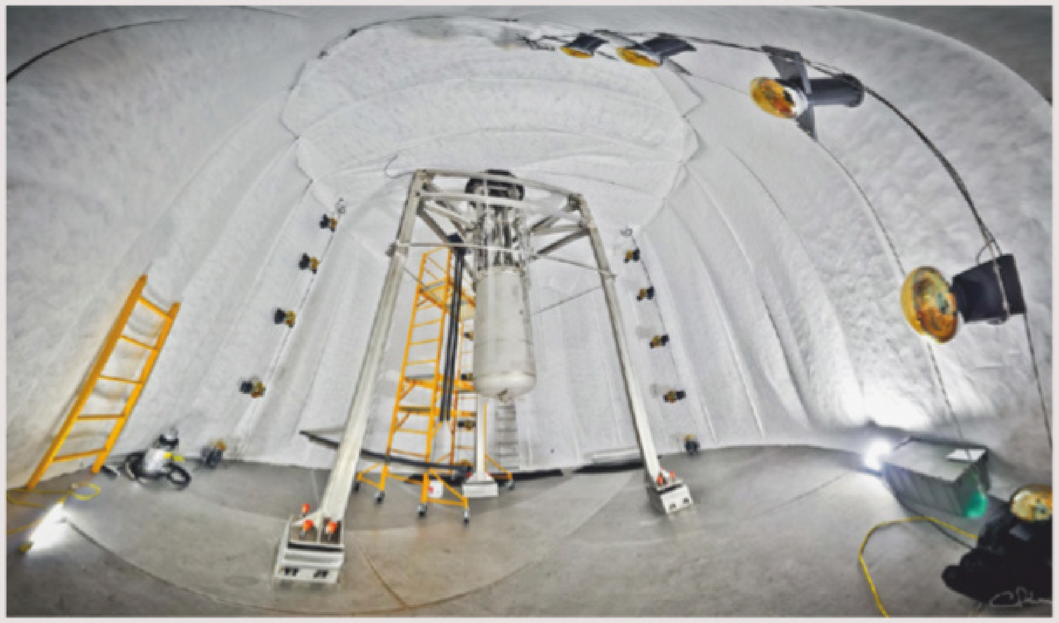
Although dark matter in galaxy clusters typically traces the ordinary matter that radiates light, ZwCl 0024+1652 goes its own way. This massive cluster sports a dark matter ring (in blue) spanning 2.6 million light-years that appears largely divorced from the visible galaxies and gas. NASA/ESA/M.J. JEE (JOHNS HOPKINS UNIVERSITY)

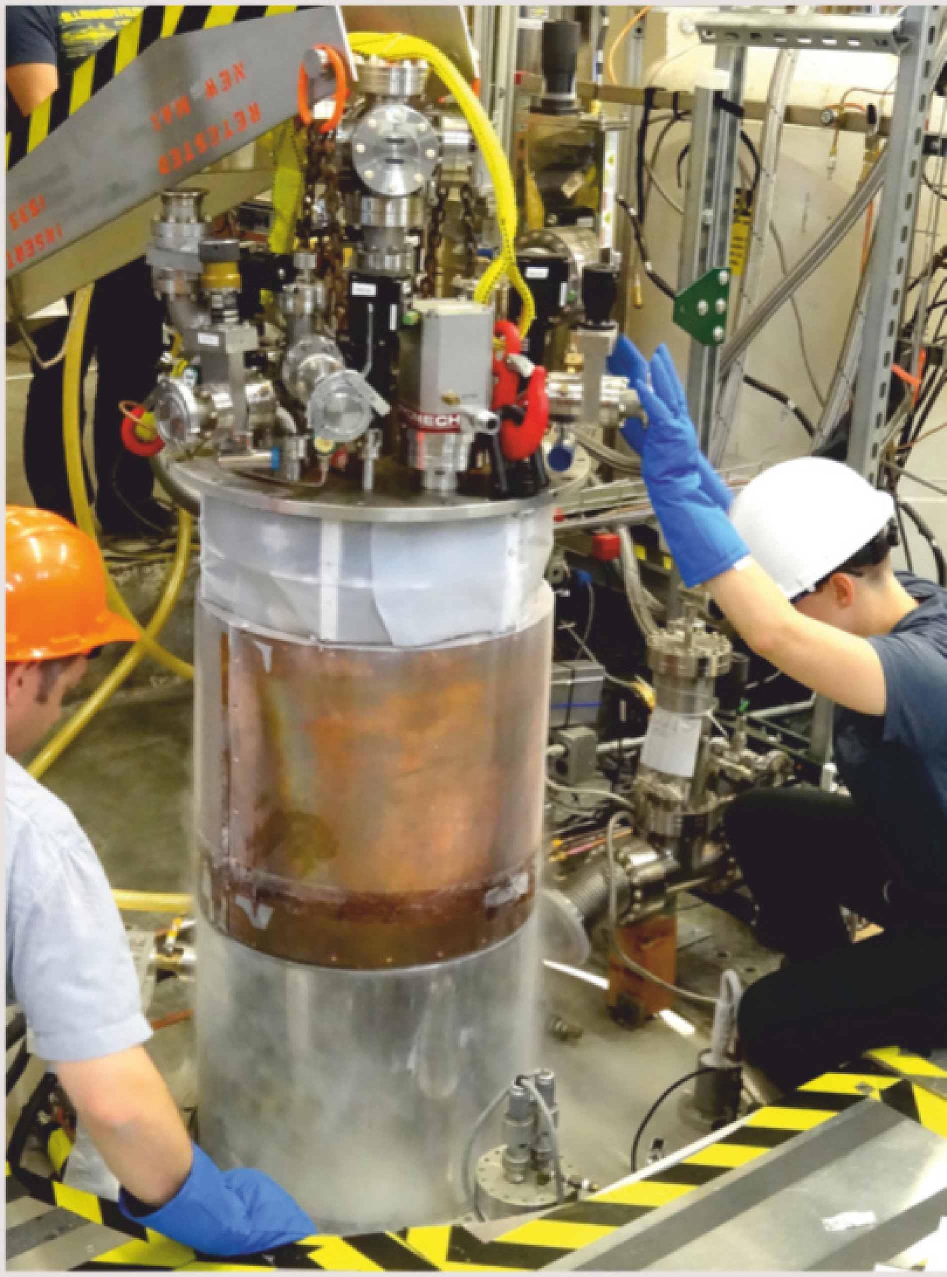
and evolved over most of its history, they know relatively little about the first seconds that followed the Big Bang — and next to nothing about the first trillionth of a second. When it comes to how our universe may have evolved, or to the events that may have taken place during these earliest moments, we have essentially no direct observations on which to rely. This era is hidden from view, buried beneath impenetrable layers of energy, distance, and time.

Our understanding of this period of cosmic history is, in many respects, little more than an informed guess based on inference and extrapolation. Look far enough back in time, and almost everything we know about our universe could have been different. Matter and energy existed in different forms than they do today, and they may have experienced forces that have not yet been discovered. Key events and transitions may have taken place that science has yet to illuminate. Matter likely interacted in ways that it no longer does, and space and time themselves may have behaved differently than they do in the world we know.

With this in mind, many cosmologists have begun to consider the possibility that our failure to detect the particles that make up dark matter might be telling us not only about the nature of dark matter itself, but also about the era in which it was created. By studying dark

Earthbound experiments on the hunt for dark matter





COUNTERCLOCKWISE FROM TOP LEFT: The IceCube Neutrino Observatory sits under South Pole ice, hunting for cosmic neutrinos. Some of these subatomic particles could come from the decay of weakly interacting massive particles — a prime candidate for dark matter — though none has been detected yet. MARTIN WOLF (ICECUBE/NSF)

The Large Underground Xenon experiment (LUX) attempted to detect interactions between weakly interacting massive particles and 816 pounds (370 kg) of liquid xenon inside this tank. The experiment, which operated from 2013 to 2016 in an old mine in the Black Hills of South Dakota, turned up none of these dark matter particles. A successor, the 7-ton LUX-ZEPLIN, should begin taking data in 2020. CARLOS FAHAM/WIKIMEDIA COMMONS

The Axion Dark Matter Experiment looks for hypothetical axions when they decay into microwaves in the presence of a strong magnetic field. Here, technicians install the superconducting magnet in a lab at the University of Washington. LAMESTLAMER/WIKIMEDIA COMMONS

matter, scientists are learning about the first moments after the Big Bang.

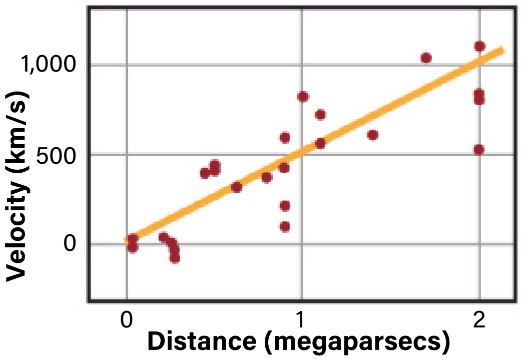
How fast is space expanding?

In 1929, Edwin Hubble discovered that galaxies are moving away from us at speeds proportional to their distances. This provided the first clear evidence that our universe is expanding. Ever since, the current rate of this expansion — the Hubble constant — has been one of the key properties of our universe that cosmologists study.

It's fair to say that the Hubble constant has long been difficult to measure. Hubble's original determination was plagued with systematic errors that led him to overestimate the expansion rate by a factor of 7. As recently as the 1990s, textbooks often quoted values ranging from as low as 50 to as high as 100 kilometers per second for every million parsecs separating two points in space — usually written as 50 to 100 km/s/Mpc. (One megaparsec [Mpc] equals 3.26 million light-years.) Although the precision of these measurements has improved considerably over the past two decades, no consensus yet exists regarding the correct value for this quantity. In fact, as these measurements have improved, the results from different methods seem to disagree with one another even more.

One way to determine the Hubble constant is to directly measure how fast objects are moving away from us, just as Hubble did in 1929. For his measurements, Hubble used a special class of pulsating stars known as Cepheid variables, whose intrinsic luminosities track nicely with the periods over which they brighten and fade. Modern cosmologists continue to use Cepheids for this purpose, but they also employ other classes of objects, including type Ia supernovae — exploding white dwarfs that all have the same approximate luminosity. When researchers combine the latest data, they find that the universe is currently expanding at a rate of about 72 to 76 km/s/Mpc.

GALAXIES IN MOTION



Edwin Hubble discovered the expanding universe in 1929, when he first plotted the velocities of individual galaxies relative to their distances. (The line gives the best fit to the data.) Although his estimated distances were a factor of nearly 10 too small, he got the basic relationship right. *ASTRONOMY*: ROEN KELLY, AFTER EDWIN HUBBLE/*PNAS* (MARCH 15, 1929)

But that's not the end of the story. Cosmologists also can infer the value of the Hubble constant by studying the primordial light released when the first atoms formed some 380,000 years after the Big Bang. The detailed temperature patterns of this light — known as the cosmic microwave background — serve as a map that shows how matter was distributed throughout the universe at that time.

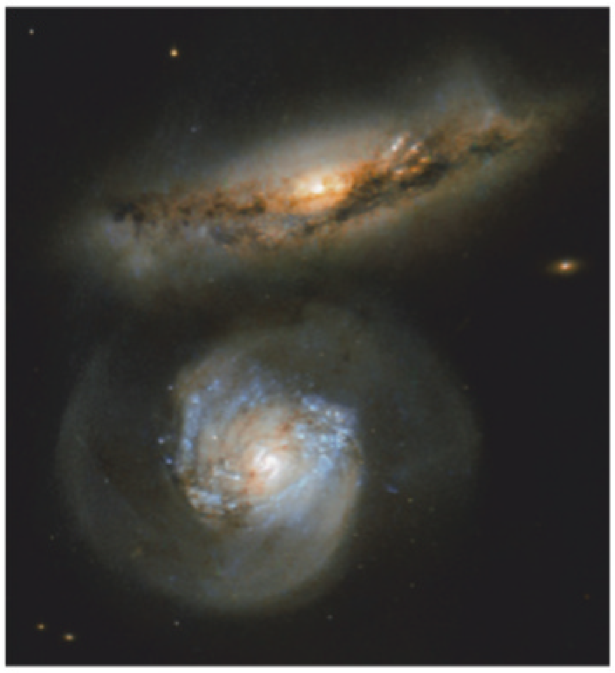
When scrutinized, this map reveals many details about our young universe, including how much matter and other forms of energy were present, as well as how fast space was expanding. It also tells us that the Hubble constant is about 67 km/s/Mpc — a significantly smaller value than cosmologists have found through more direct measurements.

What does this mismatch mean for our universe? Assuming that these studies have correctly accounted for all the systematic uncertainties inherent in the observations, these two ways of determining the Hubble constant appear to be incompatible — at least within the context of the standard cosmological model. To make these discrepant results mutually consistent, astronomers would be forced to change how we think the cosmos expanded and evolved, or to reconsider the forms of matter and energy in the universe during the first few hundred thousand years following the Big Bang.

According to Einstein's general theory of relativity, the rate at which space expands depends on the density of

The Antennae Galaxies (NGC 4038 and NGC 4039) are two interacting spirals located 65 million light-years from Earth. Host to many Cepheid variable stars as well as a type Ia supernova, the pair is one of a handful of systems that possess both types of standard candles and thus forge a link between the two. ESA/HUBBLE & NASA

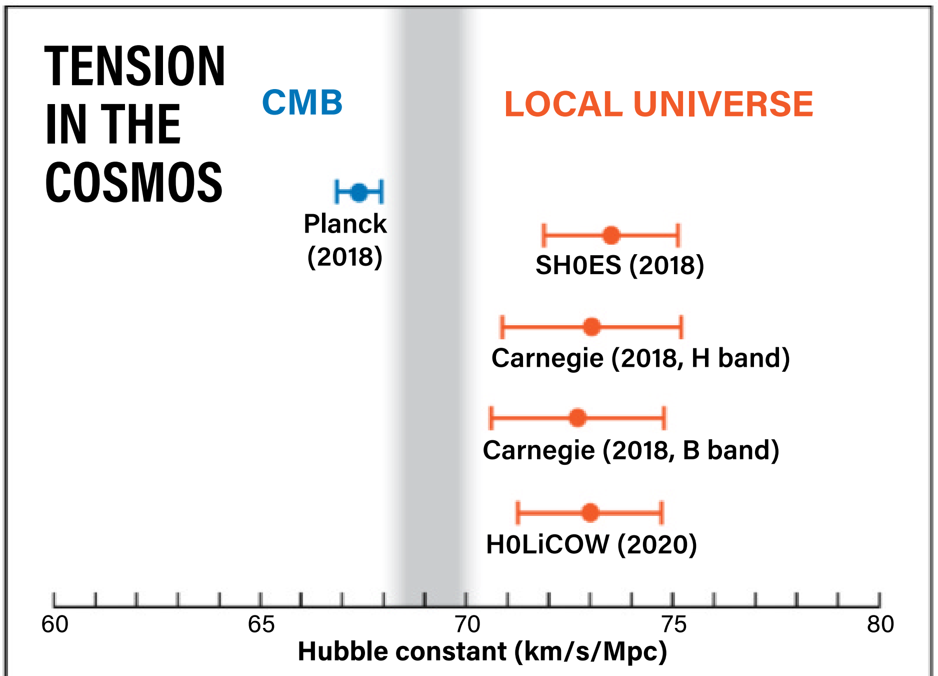
Spiral galaxy NGC 3972 forms a key link in the cosmic distance ladder. The galaxy contains dozens of Cepheid variables, which astronomers use to gauge distances to relatively nearby galaxies, and in 2011 hosted a type Ia supernova, an exploding white dwarf that serves as a vital link to finding distances to more remote galaxies. Scientists need both markers to pin down the Hubble constant. NASA/ESA/A. RIESS (STScI/JHU)



Spiral galaxy MCG+01-38-005 (the lower member of this galaxy pair) harbors a water megamaser — amplified microwave emission from water molecules — orbiting the supermassive black hole at its center. The microwave emission provides an independent way to measure the galaxy's distance and thus helps astronomers refine values for the Hubble constant. ESA/HUBBLE & NASA

A type Ia supernova exploded in the grand design spiral M100 in early February 2006. (The supernova is the brighter of the two stars to the lower right of the galaxy's center.) Supernovae of this type, which arise when a white dwarf accumulates too much mass from a binary companion, all have the same intrinsic brightness and thus make excellent distance indicators. ESO/IDA/DANISH 1.5 M/R. GENDLER, J.-E. OVALDSEN, C.C. THÖNE, AND C. FÉRON

TENSION IN THE COSMOS



Astronomers have been trying to determine the expansion rate of the cosmos for nearly a century. Although measurements of this so-called Hubble constant have grown more precise over the years, different methods yield different results. Direct observations of relatively nearby galaxies give significantly higher values than those deduced from observations of the cosmic microwave background. *ASTRONOMY*: ROEN KELLY

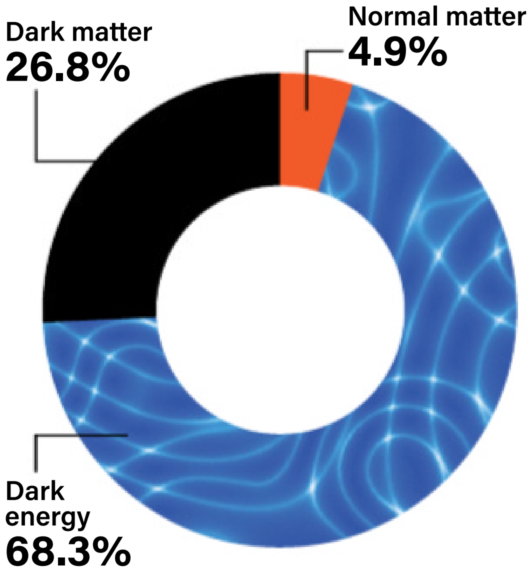
matter and other forms of energy it contains. When cosmologists infer the value of the Hubble constant from the cosmic microwave background, they have to make assumptions about the amounts of dark matter, neutrinos, and other substances that were present.

Perhaps the simplest way to explain the tension between the different measurements of the Hubble constant would be to hypothesize that the cosmos contained more energy than expected during the first hundred thousand years or so following the Big Bang. This energy might have taken the form of an exotic species of light and feebly interacting particles, or of some kind of dark energy associated with the vacuum of space itself that has long since disappeared from the universe. Or perhaps there is something else we don't understand about this era of cosmic history. We simply do not yet know how to resolve this intriguing mystery.

Is a revolution coming?

As I said earlier, it's possible that the various puzzles cosmologists face today are little more than a few trivial threads that scientists will tie up nicely in the years ahead with the help of new experiments and observations. But lately, it seems the more we study the universe, the less we understand it. Despite decades of effort, the nature of dark matter remains unknown, and the problem of dark energy seems nearly intractable. We do not know how the particles that make up the atoms in our universe managed to survive the first moments of the Big Bang, and we still know little about cosmic inflation, how it played out, or how it came to an end — assuming that something like inflation happened at all.

WHAT IS THE UNIVERSE MADE OF?

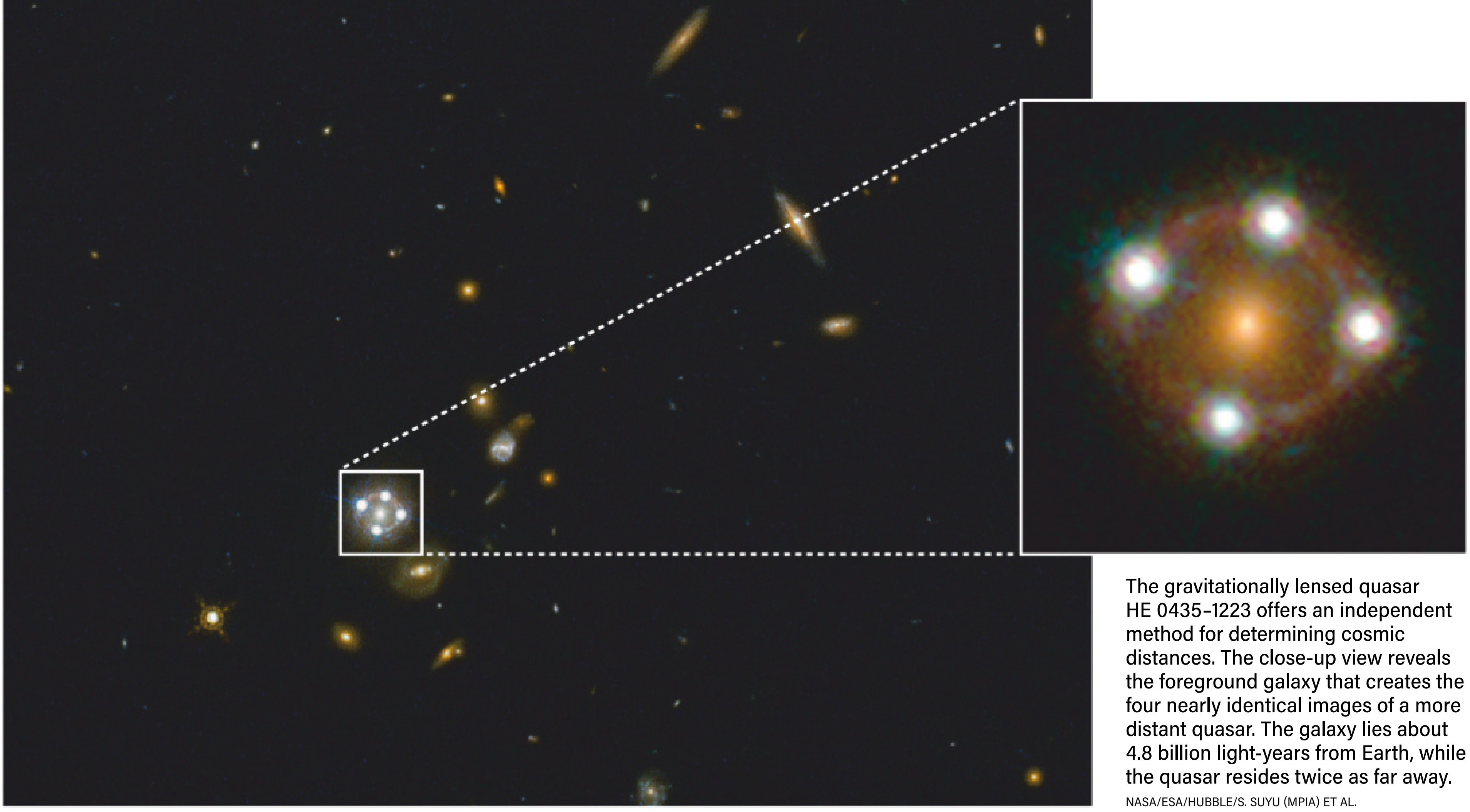


The atoms that make up stars, planets, and people add up to less than 5 percent of the universe's constituents. Invisible dark matter contributes more than five times as much, while the dark energy that powers the accelerating cosmos accounts for more than two-thirds of the total. *ASTRONOMY*: ROEN KELLY

It is from this perspective that I sometimes find myself considering whether these mysteries might represent something greater than a few open and unrelated questions. Perhaps they are telling us that the earliest moments of our universe were far different from what we long imagined them to be. Perhaps these problems represent the beginning of a revolution for the science of cosmology.

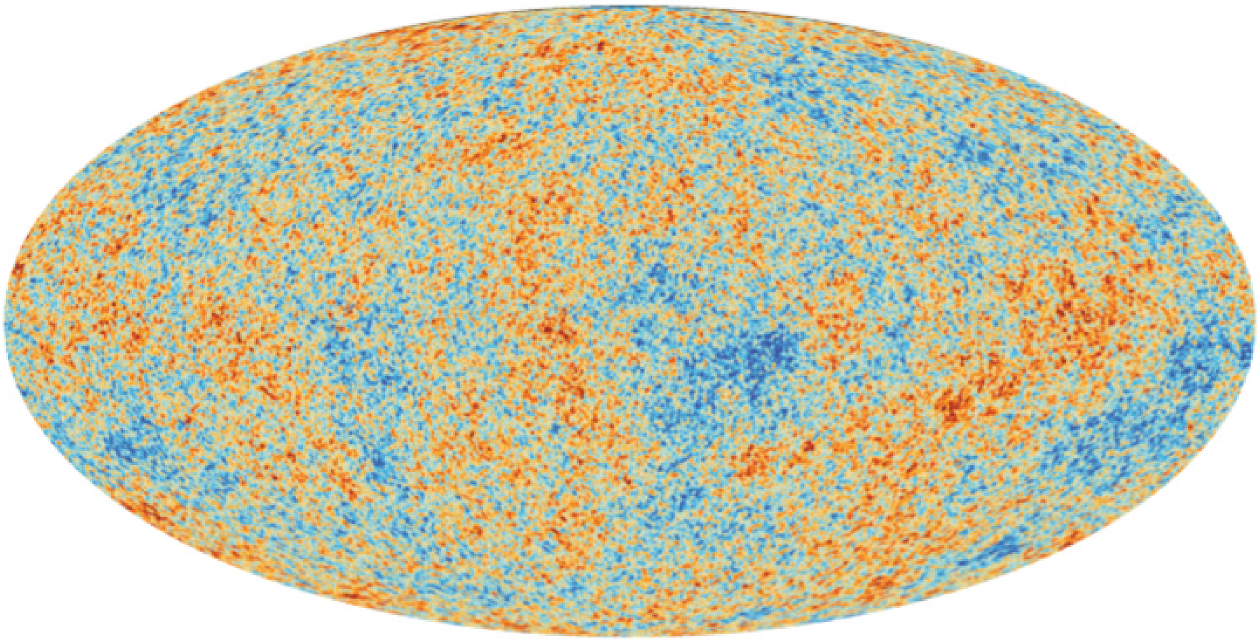
Sometimes I wonder whether we might be on a significant precipice of scientific history, similar to what we experienced in 1904. At that time, physics had never before seemed to be on such solid footing. For more than two centuries, the principles of Newtonian physics had been applied successfully to problem after problem. And although physicists expanded their knowledge into areas such as electricity, magnetism, and heat, these aspects of the world were really not so different from those Newton had described hundreds of years earlier. To the physicists of 1904, the world seemed well understood. There was little reason to expect a revolution.

Similar to the situation cosmologists confront today, however, the physicists of 1904 had not yet been able to address a few challenges. The medium through which they believed light traveled — the luminiferous ether — should have induced variations in the speed of light, and yet light always moves through space



The gravitationally lensed quasar HE 0435–1223 offers an independent method for determining cosmic distances. The close-up view reveals the foreground galaxy that creates the four nearly identical images of a more distant quasar. The galaxy lies about 4.8 billion light-years from Earth, while the quasar resides twice as far away.

NASA/ESA/HUBBLE/S. SUYU (MPIA) ET AL.



The European Space Agency's Planck satellite has captured the best data on the cosmic microwave background radiation. Combining these results with the standard model describing the universe produces a Hubble constant that is slightly but unequivocally smaller than that gleaned from nearby galaxies.

ESA/PLANCK COLLABORATION

at the same rate. Astronomers observed the orbit of Mercury to be slightly different from what Newtonian physics predicted, leading some to suggest that an unknown planet, dubbed Vulcan, might be perturbing Mercury's trajectory.

Physicists in 1904 had no idea what powered the Sun — no known chemical or mechanical process could possibly generate so much energy over such a long time. Lastly, scientists knew various chemical elements emitted and absorbed light with specific patterns, none of which physicists had the slightest idea how to explain. In other words, the inner workings of the atom remained a total and utter mystery.

Although few saw it coming, in hindsight, it's clear that these problems were heralds of a revolution in physics. And in 1905, the revolution arrived, ushered in by a young Albert Einstein and his new theory of relativity. We now know that the luminiferous ether does not exist and that there is no planet Vulcan. Instead, these fictions were symptoms of the underlying failure of Newtonian physics. Relativity beautifully solved and explained each of these mysteries without any need for new substances or planets.

Furthermore, when scientists combined relativity with the new theory of quantum physics, it became possible to explain the Sun's longevity, as well as the inner workings of atoms. These new theories even opened doors to new and previously unimagined lines of inquiry, including that of cosmology itself.

Scientific revolutions can profoundly transform how we see and understand our world. But radical change is never easy to see coming. There is probably no way to tell whether the mysteries faced by cosmologists today are the signs of an imminent scientific revolution or merely the last few loose ends of an incredibly successful scientific endeavor.

There is no question that we have made incredible progress in understanding our universe, its history, and its origin. But it is also undeniable that we are profoundly puzzled, especially when it comes to the earliest moments of cosmic history. I have no doubt that these moments hold incredible secrets, and perhaps the keys to a new scientific revolution. But our universe holds its secrets closely. It is up to us to coax those secrets from its grip, transforming them from mystery into discovery.

Dan Hooper *is a senior scientist at the Fermi National Accelerator Laboratory in Illinois and a professor of astronomy and astrophysics at the University of Chicago. He is author of* At the Edge of Time: Exploring the Mysteries of Our Universe's First Seconds.

DARK M shadowy effect on Earth

Earth's periodic passage through the galaxy's disk could initiate a series of events that ultimately lead to geological cataclysms and mass extinctions.

by Michael R. Rampino

Do geologists dream of a final theory? Most people would say that plate tectonics already serves as geology's overarching idea. The discovery of plate tectonics 50 years ago was one of the great scientific achievements of the 20th century, but is the theory complete? I think not. Plate tectonics describes Earth's present geology in terms of the geometry and interactions of its surface plates. Geologists can extrapolate plate motions both back in time and into the future, but they cannot yet derive the behavior and history of plate tectonics from first principles.

Although scientists can interpret the history through the lens of what they see today, an important question remains: Why did geologic events — such as hot-spot volcanism, the breakup of continents, fluctuations in seafloor spreading, tectonic episodes, and sea-level oscillations — occur exactly when and where they did? Are they random, or do they follow some sort of a pattern in time or space?

A complete theory of Earth should explain geologic activity in the spatial domain, as plate tectonics does quite well for the present (once you incorporate hot spots), but also in the time and frequency domains. Recent findings suggest to me that geology may be on the threshold of a new theory that seeks to explain Earth's geologic activity in time and space in the context of its astronomical surroundings.

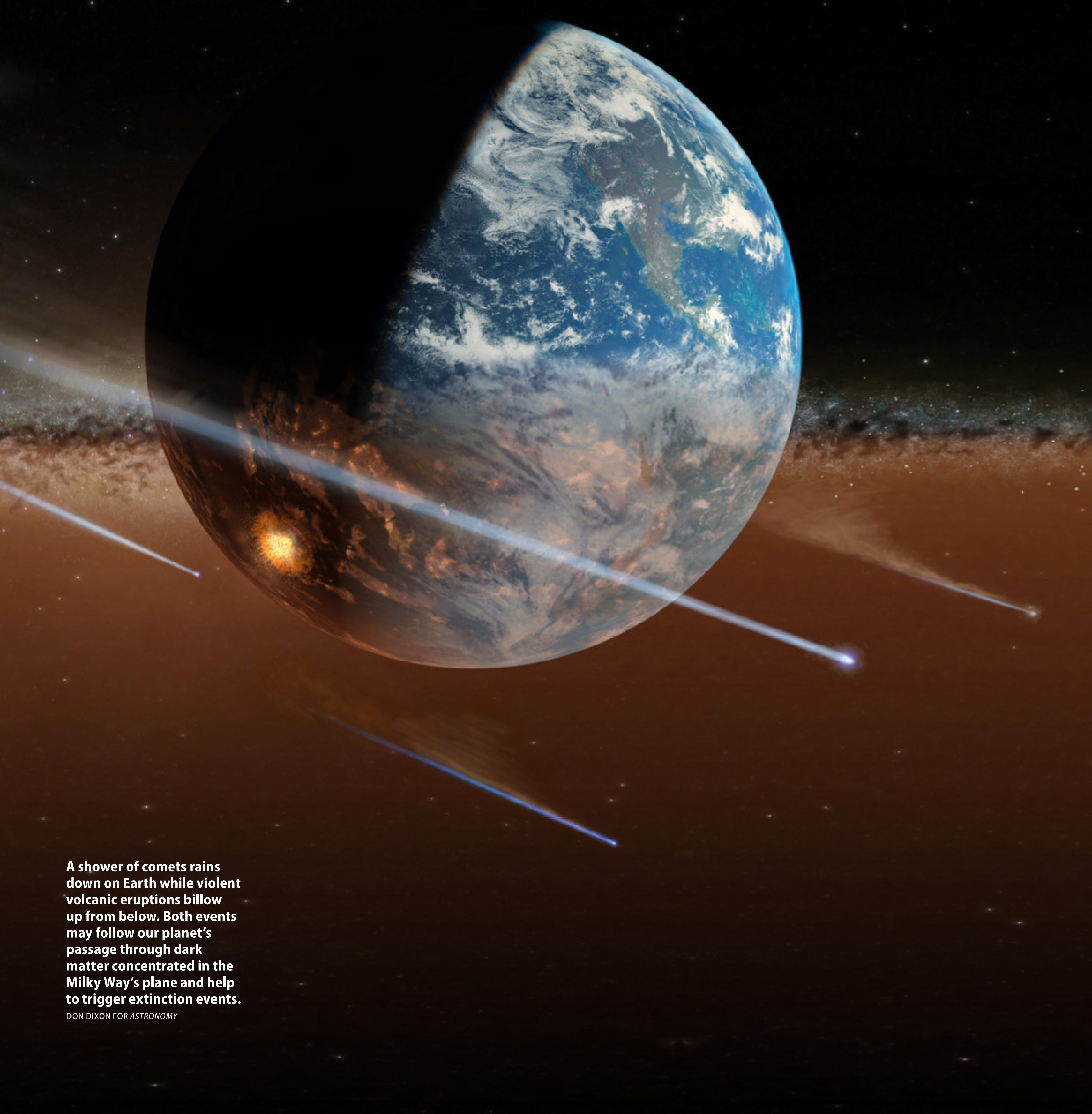
A big impact

The first clue for a cosmic connection came in a 1980 report by Nobel Prize-winning physicist Luis Alvarez and his son Walter, a noted geologist. Working at the University of California, Berkeley, the two suggested that the severe mass extinction of life at the end of the Cretaceous period 66 million years ago was the result of a devastating impact of a large asteroid or comet. This spectacular finding was followed in early 1984 with the remarkable claim by Dave Raup and Jack Sepkoski of the University of Chicago that mass-extinction events followed a 26-million-year cycle.

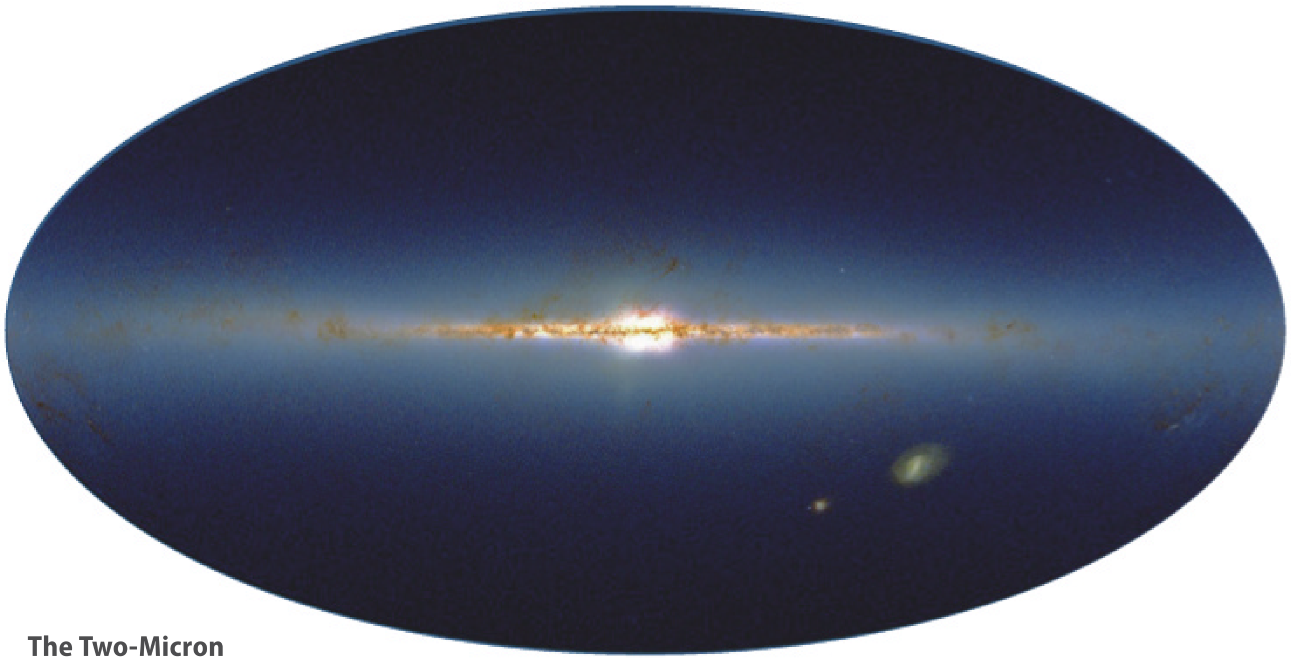
Could periodic impacts cause periodic extinctions? A number of craters of various sizes and ages mark the location of past impacts, and the estimated ages of several coincide fairly well with mass extinctions. For example, Nobel laureate Harold Urey noted in 1973 that the 56-mile-diameter (90 kilometers) Popigai crater in northern Siberia dates from about 36 million years ago, close to the time of the Late Eocene extinction event.

Cratering specialist Richard Grieve of the Canadian Bureau of Mines and Energy in Ottawa originally compiled the most complete list of terrestrial impact craters. (The ever-growing list

ATTER'S



A shower of comets rains down on Earth while violent volcanic eruptions billow up from below. Both events may follow our planet's passage through dark matter concentrated in the Milky Way's plane and help to trigger extinction events.
DON DIXON FOR *ASTRONOMY*



The Two-Micron All-Sky Survey revealed what the Milky Way looks like edge-on. Clearly visible is the dark horizontal band marking the galaxy's midplane. Earth's passage through this region every 30 million years or so could initiate a series of events that leads to extinction events on Earth. 2MASS/IPAC/CALTECH

is now maintained online.) The Earth Impact Database currently contains about 190 documented impact craters, and includes their sizes, locations, and estimates of their ages. These craters are only a small subset of the actual number of objects that have collided with Earth. Many more impact craters have been so severely eroded and/or covered by sediments that they are difficult to identify. What's more, no craters have been found in the deep ocean, only in shallow areas of the continental shelf. This is not surprising because the ocean floor is young, at most only about 180 million years old, so it should exhibit relatively few craters. And no one knows precisely what kind of structure a large impact into thin ocean crust would leave behind.

Many of the estimates of crater ages are merely rough limits based on the age of the older rocks targeted by the impact, or the age of the first sediments burying the impact structure. But a number of the craters have been dated well enough by studying the decay of the impactor's radioactive elements to make a rigorous statistical analysis of the timing of the impacts. In the mid-1980s, the ages of the best-dated craters in Grieve's list were run through the computer at NASA's Goddard Institute for Space Studies in New York City using a new analysis method, and the impact-crater record showed a significant periodicity of about 30 million years.

At the same time, Walter Alvarez and physicist Richard Muller, also at UC Berkeley, did their own analysis and found a 28-million-year cycle using a somewhat different set of craters. Other researchers have revisited these results over the years, and they are still controversial. But in 2015, my former student Ken Caldeira and I studied more impact structures with improved crater-age data and were able to be more specific. We found that craters and extinctions both seem to occur with the same 26-million-year cycle.

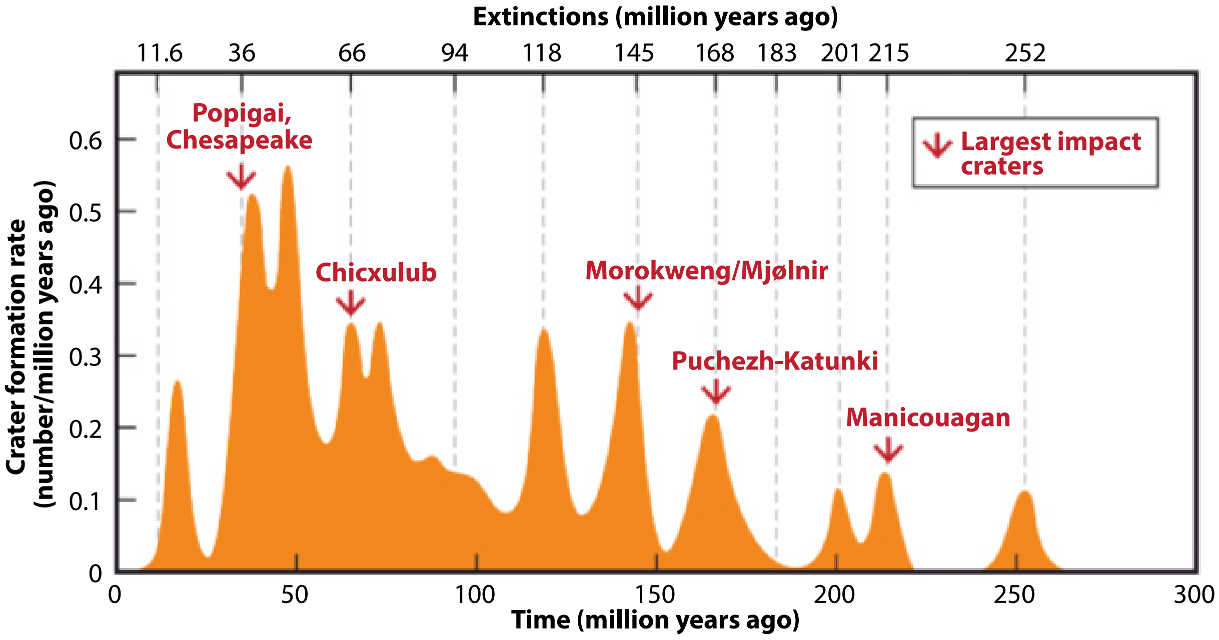
These analyses of crater ages convinced me that many of the impacts were periodic. Still, it begged the question of where they were coming from. There were two possibilities: Earth-crossing asteroids originally from the asteroid belt between the orbits of Mars and Jupiter, or icy comets from the distant Oort Cloud that surrounds the Sun. We doubted that asteroids could have pelted Earth in regular cycles. That left the Oort Cloud comets, which number in the trillions. In the early 1980s, astronomer Jack Hills of Los Alamos National Laboratory in New Mexico calculated that a passing star could induce gravitational perturbations that would shake up the loosely bound Oort Cloud comets at the edge of the solar system. This would cause large numbers of these icy bodies to fall into the inner solar system, producing a comet shower, where some could strike Earth. Hills even suggested that such a comet shower could have caused the demise of the dinosaurs. But if comet showers were the culprits, why would they show a cycle of 26 million to 30 million years?

A galactic connection

It seemed natural to search for any cosmic cycles that have a period of about 30 million years. One in particular stands out. The solar system oscillates with respect to the midplane of the disk-shaped Milky Way Galaxy with a period of about 60 million years. The Sun's family passes through this plane twice each period, or once every 30 million years or so. The solar system behaves like a horse on a carousel — as we go around the disk-shaped galaxy, we bob up and down through the disk, passing through its densest part roughly every 30 million years.

Considering possible errors in dating the extinctions and the craters, as well as the uncertainties in the galactic period, the three cycles seemed to agree. Surely, it is too much of a coincidence that the cycle found in mass extinctions and impact craters should turn out to be one of the fundamental periods of our galaxy. The idea seemed almost too pretty to be wrong. But people searching for cycles have been fooled before, and we still had to answer

An impact on extinctions



The crater formation rate ebbs and flows with time, though most often it peaks close to the time of an extinction event. The highlighted events indicate the six largest impacts during the past 260 million years. *ASTRONOMY*: ROEN KELLY, AFTER RAMPINO, CALDEIRA, AND PROKOPH

The edge-on spiral NGC 1055 in Cetus reveals the thick bands of gas and dust that pervade a typical spiral galaxy's disk. The mass concentrated there can jostle distant comets and send them hurtling toward their stars. ESO

Comet Hale-Bopp mesmerized observers when it passed through the inner solar system in 1997. This first-time visitor from the distant Oort Cloud had a nucleus some 37 miles (60 km) across — big enough to cause catastrophic damage if it hit Earth. Similar comets of the past may have initiated mass extinctions. GERALD RHEMANN

the question: How does this cycle of movement lead to periodic perturbations of the Oort Cloud comets?

Obviously, whatever object or objects was causing a periodic gravitational perturbation strong enough to disturb Oort Cloud comets would have to be quite massive. Hills had suggested that a star could do the trick. However, close encounters with stars should not take place as often as once every 30 million years. Massive interstellar clouds of gas and dust might be a better alternative. A close encounter with a large cloud — say, one with a mass greater than 10,000 times that of the Sun — also could deliver a comet shower.

A large fraction of our galaxy's normal matter resides in a flattened disk. Using computer simulations of galactic motion, physicist John Matese at the University of Louisiana and his colleagues calculated that the Oort Cloud would be especially vulnerable to gravitational perturbations caused by galactic tides — in essence, the pull of gravity of all the mass concentrated in the midplane. And a comparison of the estimated times when the solar system crossed the galactic plane with the times of impacts and mass extinctions showed potential correlations.

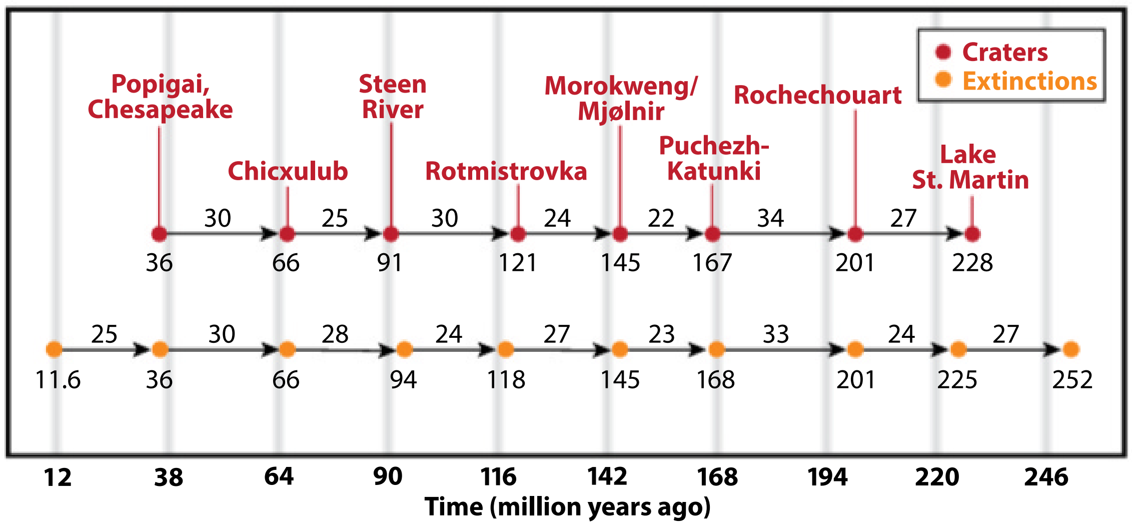
A dark matter connection?

More recently, in 2014, astrophysicists Lisa Randall and Matthew Reece at Harvard University suggested that the largest gravitational perturbations of the Oort Cloud could be from an invisible thin disk of exotic dark matter. Astronomers believe dark matter — a mysterious form of matter that interacts only through the gravitational force — accounts for about 85 percent of all the matter in the universe. Amazingly, all the visible matter in planets, stars, nebulae, and galaxies makes up only 15 percent of the total.

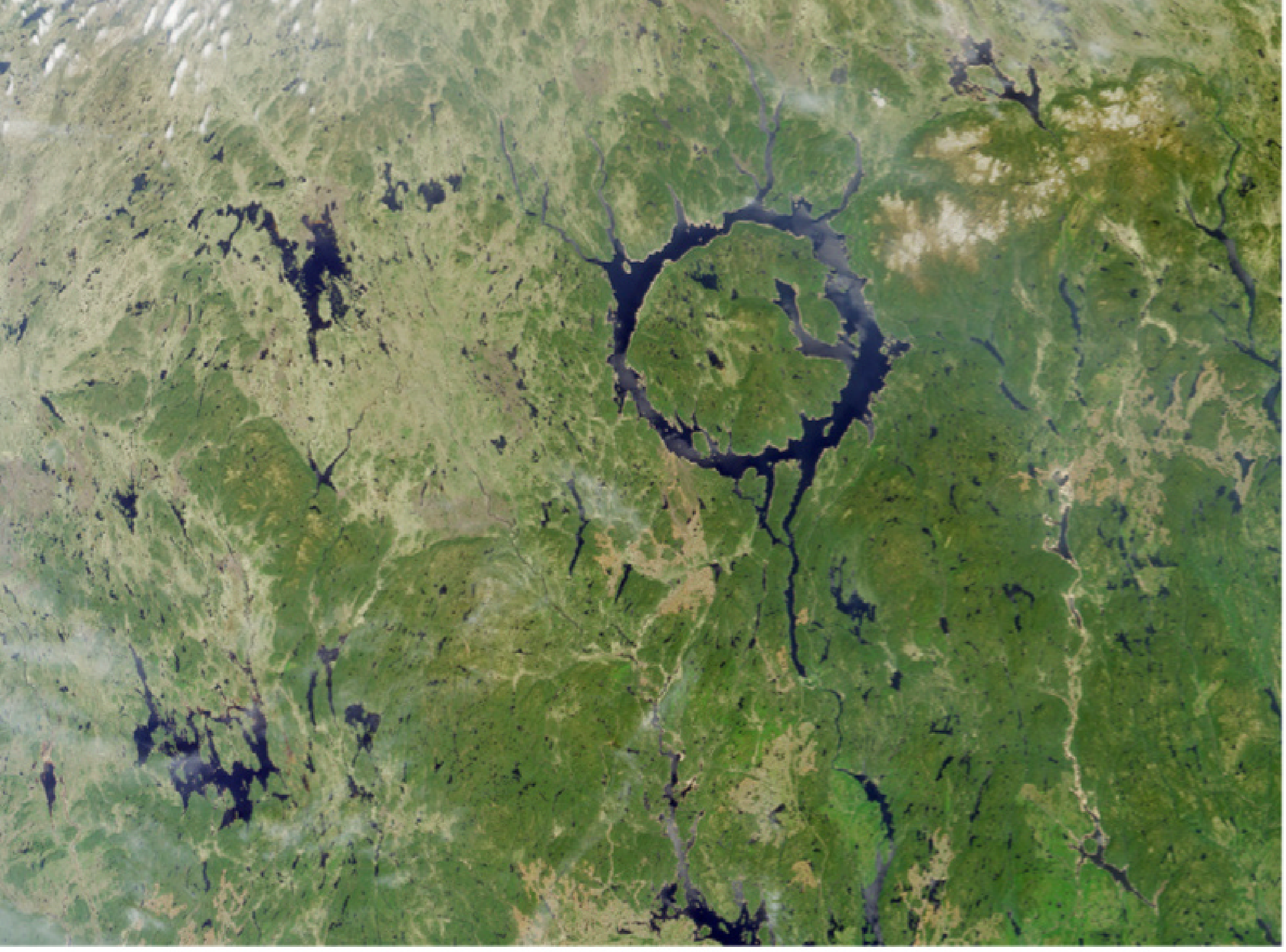
Evidence for dark matter comes mostly from the motions of galaxies. Dark matter explains the fact that stars far from the centers of rotating galaxies have much higher velocities than predicted from the distribution of visible matter alone. Without some additional matter exerting a gravitational pull, the galaxies would fly apart. To explain the "excess velocity" of the stars, scientists think the dark matter likely forms a spherical halo surrounding the galaxies. Evidence for dark matter also comes from galaxy clusters, which require far more matter than what is visible to produce the gravitational forces holding the clusters together. Dark matter also makes its presence known through gravitational lensing. The dark matter halo of a nearby galaxy distorts the light from background galaxies into a ring of mirages around the closer galaxy.

Most astrophysicists believe that dark matter is likely composed of weakly interacting massive particles or axions. But whatever it is, dark matter does not interact with electromagnetic radiation, so it is difficult to detect. Although scientists infer that dark matter resides in spherical halos surrounding spiral galaxies like our own, Randall and Reece suggested that some dark matter also would be concentrated in a thin disk along the galaxy's midplane.

A match made in the heavens?



The relationship between extinction events nicely tracks with the geological record of major "periodic" craters formed from large comet or asteroid impacts. Here, we plot the accepted extinction events (orange circles) and the times between each below the major periodic craters (red circles) and the gaps between them, and compare those with a 26 million-year cycle that started 12 million years ago. *ASTRONOMY*: ROEN KELLY, AFTER RAMPINO, CALDEIRA, AND PROKOPH



Lake Manicouagan in Quebec is the remnant of one of the largest impact features left on Earth. The crater spans about 53 miles (85 km) and resulted from an impact some 215 million years ago.
NASA/GSFC/LaRC/JPL/MISR TEAM

Some researchers predict that such a disk naturally will fragment into smaller, denser clumps. A future test for the existence of a dark matter disk will rely on new data coming from the European Space Agency's Gaia spacecraft, which is measuring the motions of stars in the galactic plane. The behavior of these stars depends on the total mass in the galaxy's disk, which should tell us how much — if any — dark matter is present.

Randall and Reece hypothesize that when the solar system passes through the densely populated galactic midplane, the concentrated gravitational force of the dark and visible mass jostles the Oort Cloud. This sends a shower of comets toward the inner solar system about every 26 million to 30 million years, where some eventually hit Earth. Where are we in this cycle today? We have just crossed the galactic midplane from "below" and remain relatively close to it. And it takes more than a million years for a comet to fall from the distant Oort Cloud into the inner solar system. This puts us in a precarious position, but it is in line with the ages of several young craters and impact-produced ejecta layers in the past 1 million to 2 million years.

Do Earth's cycles match?

But Earth's cosmic connection may go even deeper. The idea of a roughly 30-million-year rhythm in geologic events has a long history in the geological literature. In the early 20th century, A.W. Grabau, an expert on sedimentary strata, proposed that tectonic activity and mountain building drove periodic fluctuations in sea level with an approximately 30-million-year cycle. In the 1920s, noted British geologist Arthur Holmes, armed with a few age determinations from radioactive decay, saw a similar 30-million-year cycle in Earth's geologic activity.

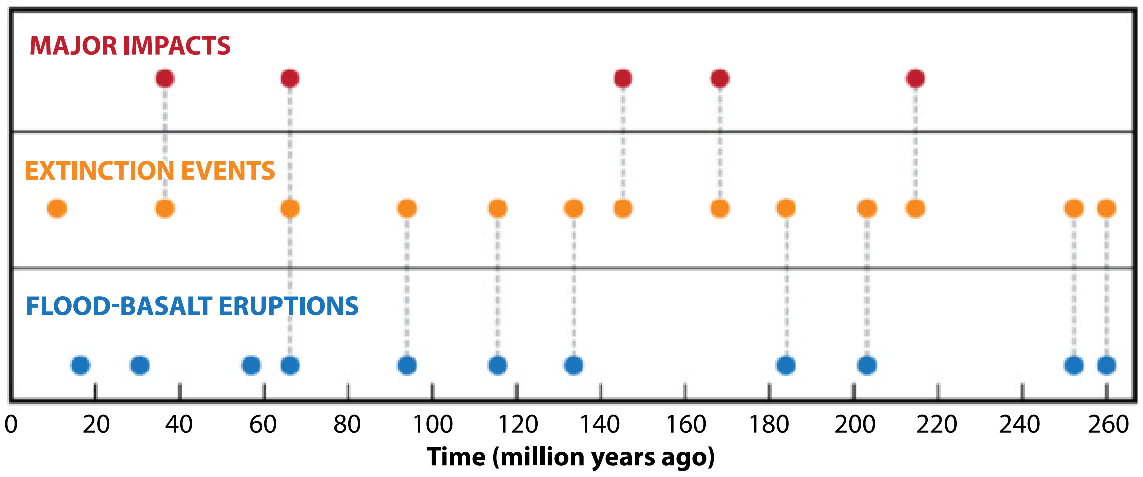
But the idea of periodicity in the geologic record later fell out of favor, and most geologists rejected the notion as simply the human propensity for seeing cycles where there are none. Today, the majority of earth scientists believe that the geologic record preserves the workings of an essentially random system. The geologic community is generally averse to the idea of regular long-term cycles. This is a result, in part, of the many papers over the years that claimed to find one period or another in the geologic record, but which did not survive closer scrutiny.

I spent a lot of time in the library and online searching page by page through the major journals for data sets related to geologic changes in sea level, tectonics, various kinds of volcanism, variations in seafloor spreading rates, extinction events, and indicators of ancient climate shifts. (The last of these show up, for example, in the presence of stagnant oceans depleted in dissolved oxygen or the occurrence of major salt deposits indicating a hot, dry climate.) Eventually, I was able to recognize 77 such documented events in Earth's history over the past 260 million years.

Caldeira, my former student who is now at Stanford University, and I analyzed the new compilation of data and found a strong 26-million- to 27-million-year period of repetition. Richard Stothers at NASA did the same for geomagnetic reversals and detected an approximately 30-million-year cycle. I admit that the reality of these cycles has been much debated, and further statistical tests have produced mixed results. One problem may be that it is difficult to extract cycles from data sets that contain both periodic and nonperiodic events, as would be the case for these geologic events.

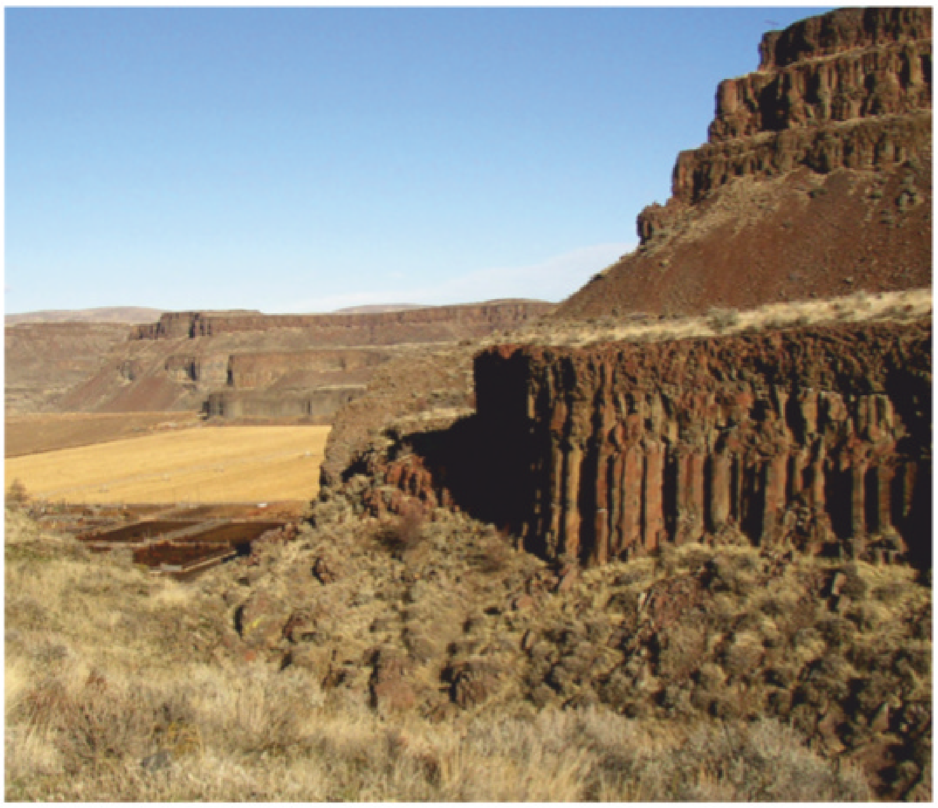
But if the cycles are real, what could be driving these long-term changes in volcanism, tectonics, sea level, and climate at such regular, if widely spaced, intervals? At first, I thought that the periodic energetic impacts might somehow be affecting deep-seated geological processes. I suggested in a short note in the journal *Nature* that large impacts might so deeply excavate and fracture the crust — to depths in excess of 10 miles (16 km) — that the sudden release

Making a significant connection



Most extinction events in the past 260 million years nearly coincide with either a major impact or a flood-basalt eruption. These events seem to repeat with a period between 26 million and 30 million years. *ASTRONOMY*: ROEN KELLY, AFTER RAMPINO, CALDEIRA, AND PROKOPH

The Piton de la Fournaise volcano on the island Réunion in the western Indian Ocean ranks among the world's most active. It lies above a hot spot in Earth's mantle and exudes low-viscosity lava that flows easily. Even larger eruptions — perhaps triggered by heat from dark matter annihilation in Earth's core — may lead to extinctions. JULIENGRONDIN/DREAMSTIME



Robust volcanic activity releases vast quantities of basaltic lava that can cover wide areas up to a mile or more deep. This view shows the characteristic stair-step formations in part of the Columbia River Basalt Group in Washington. The area formed from lavas erupted by the Yellowstone hot spot roughly 15 million years ago. WILLIAMBORG/WIKIMEDIA COMMONS

of pressure in the upper mantle would result in large-scale melting. This would lead to the production of massive flood-basalt lavas, which would cover the crater and possibly create a mantle hot spot at the site of the impact. Hot spots could lead to continental breakup, which can cause increased tectonics and changes in ocean-floor spreading rates, and in turn cause global sea levels to fluctuate. Unfortunately, no known terrestrial impact structure has a clear association with volcanism, although some volcanic outpourings on Mars seem to be located along radial and concentric fractures related to large impacts.

Trapped in the core

The potential key to resolving this geological conundrum may come from outer space. Remember that Randall and Reece suggested that Earth passes through a thin disk of dark matter concentrated along the Milky Way's midplane every 30 million years or so. Astrophysicist Lawrence Krauss and Nobel Prize-winning physicist Frank Wilczek of Harvard University, and independently Katherine Freese, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics, proposed that Earth could capture dark matter particles that would accumulate in the planet's core. The number of dark matter particles could grow large enough so that they would undergo mutual annihilation, producing prodigious amounts of heat in Earth's interior.

A 1998 paper in the journal *Astroparticle Physics* (which I am sure few geologists ever read) provided a potential missing link. Indian astrophysicists Afsar Abbas and Samar Abbas (father and son, respectively) at Utkal University also were interested in dark matter and its interactions with our planet. They calculated the amount of energy released by the annihilation of dark matter captured by Earth during its passage through a dense clump of this material. They found that mutual destruction among the particles could produce an amount of heat 500 times greater than Earth's normal heat flow, and much greater than the estimated power required in Earth's core to generate the planet's magnetic field. Putting together the predicted 30-million-year periodicity in encounters with dark matter with the effects of Earth capturing this unstable matter produces a plausible hypothesis for the origin of regular pulses of geologic activity.

Excess heat from the planet's core can raise the temperature at the base of the mantle. Such a pulse of heat might create a mantle plume, a rising column of hot mantle rock with a broad head and narrow tail. When these rising plumes penetrate Earth's crust, they create hot spots, initiate flood-basalt eruptions, and commonly lead to continental fracturing and the beginning of a new episode of seafloor spreading. The new source of periodic heating by dark matter in our planet's interior could lead to periodic outbreaks of mantle-plume activity and changes in convection patterns in Earth's core and mantle, which could affect global tectonics, volcanism, geomagnetic field reversals, and climate, such as our planet has experienced in the past.

These geologic events could lead to environmental changes that might be enough to cause extinction events on their own. A correlation of some extinctions with times of massive volcanic outpourings of lava supports this view. This new hypothesis links geologic events on Earth with the structure and dynamics of the Milky Way Galaxy.

It is still too early to tell if the ingredients of this hypothesis will withstand further examination and testing. Of course, correlations among geologic events can occur even if they are not part of a periodic pattern, and long-term geological cycles may exist apart from any external cosmic connections. The virtue of the galactic explanation for terrestrial periodicity lies in its universality — because all stars in the galaxy's disk, many of which harbor planets, undergo a similar oscillation about the galactic midplane — and in its linkage of biological and geological evolution on Earth, and perhaps in other solar systems, to the great cycles of our galaxy.

Michael R. Rampino *is professor of biology and environmental studies at New York University, and a consultant at NASA's Goddard Institute for Space Studies in New York City.*

This article is excerpted and adapted from Cataclysms: A New Geology for the Twenty-First Century *(Columbia University Press, 2017).*

SUPER

NOVA 1987A 30 years later

When a blue supergiant star lit up the southern sky, astronomers used it to learn how massive stars explode. **by Liz Kruesi**

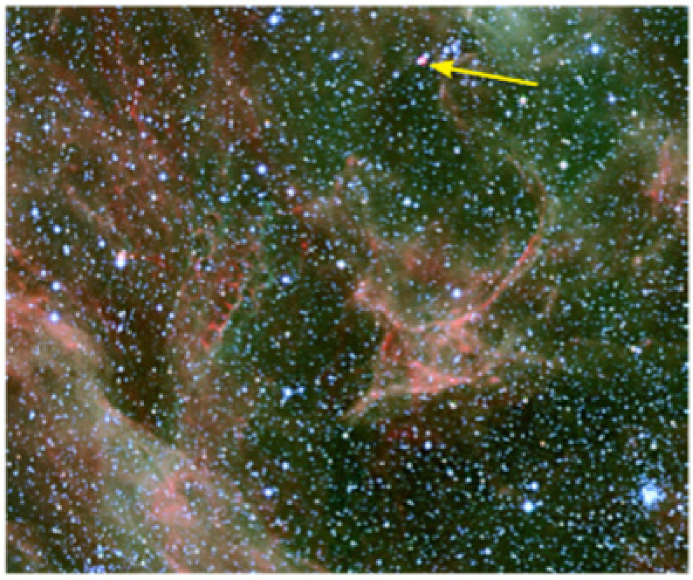
The first naked-eye supernova in nearly 400 years lit up the southern skies in February 1987. The blast occurred in the Large Magellanic Cloud, a Milky Way satellite galaxy, not far from the massive Tarantula Nebula to its upper left. ESO

Astronomy doesn't adhere to humans and their timescales. Cosmic objects typically take thousands, millions, or even billions of years to evolve. But every so often, the universe gifts us an exception. A brilliant explosion that appeared in our sky over 30 years ago is one such present.

This cosmic object, Supernova 1987A, marked the death of a massive star. The glowing ember lies 160,000 light-years from Earth in the Milky Way's largest satellite galaxy, the Large Magellanic Cloud (LMC). In astronomical terms, that's next door. This proximity means that our telescopes can resolve small changes in the evolving supernova remnant, changes that would be invisible if the object lay millions of light-years away.

"It changes on human timescales," says Penn State astrophysicist Kari Frank. That uniqueness is what keeps her and the hundreds of other astronomers who study SN 1987A interested in this object.

Supernovae happen, on average, once per century in a galaxy the size of the Milky Way, although our galaxy is long overdue. So we welcome our galactic neighbor's gift. With observations tracking every step of this supernova's evolution as it transitions from blast to remnant, astronomers are piecing together details of the explosion itself and the star that gave birth to it. Scientists can't obtain these types of details for any other supernova, which makes SN 1987A not just an exciting cosmic object but also one that reveals characteristics of an entire class.

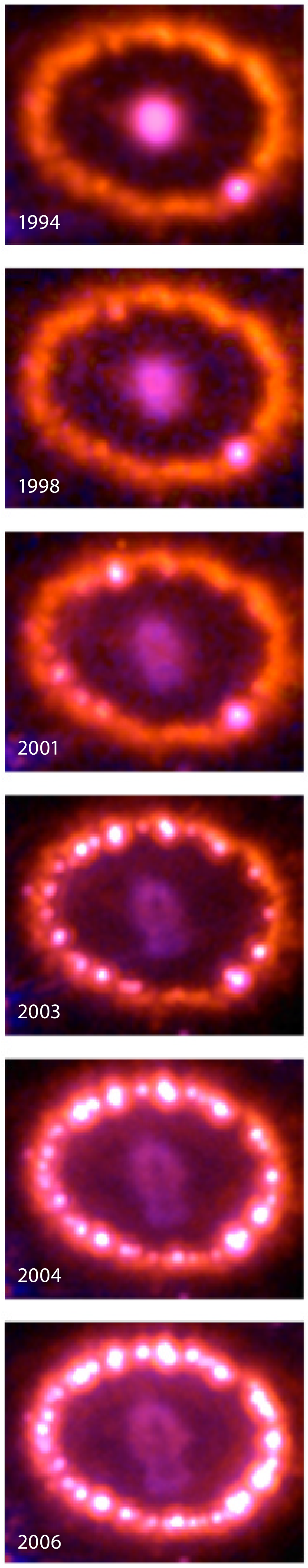


The tiny purplish splotch (arrow) at the top of this image marks the site of Supernova 1987A and its expanding debris in 2006. The intricate folds of the Honeycomb Nebula appear at center left. ESO

After watching the continually evolving glow of SN 1987A in every type of light for three decades, this is what we now know.

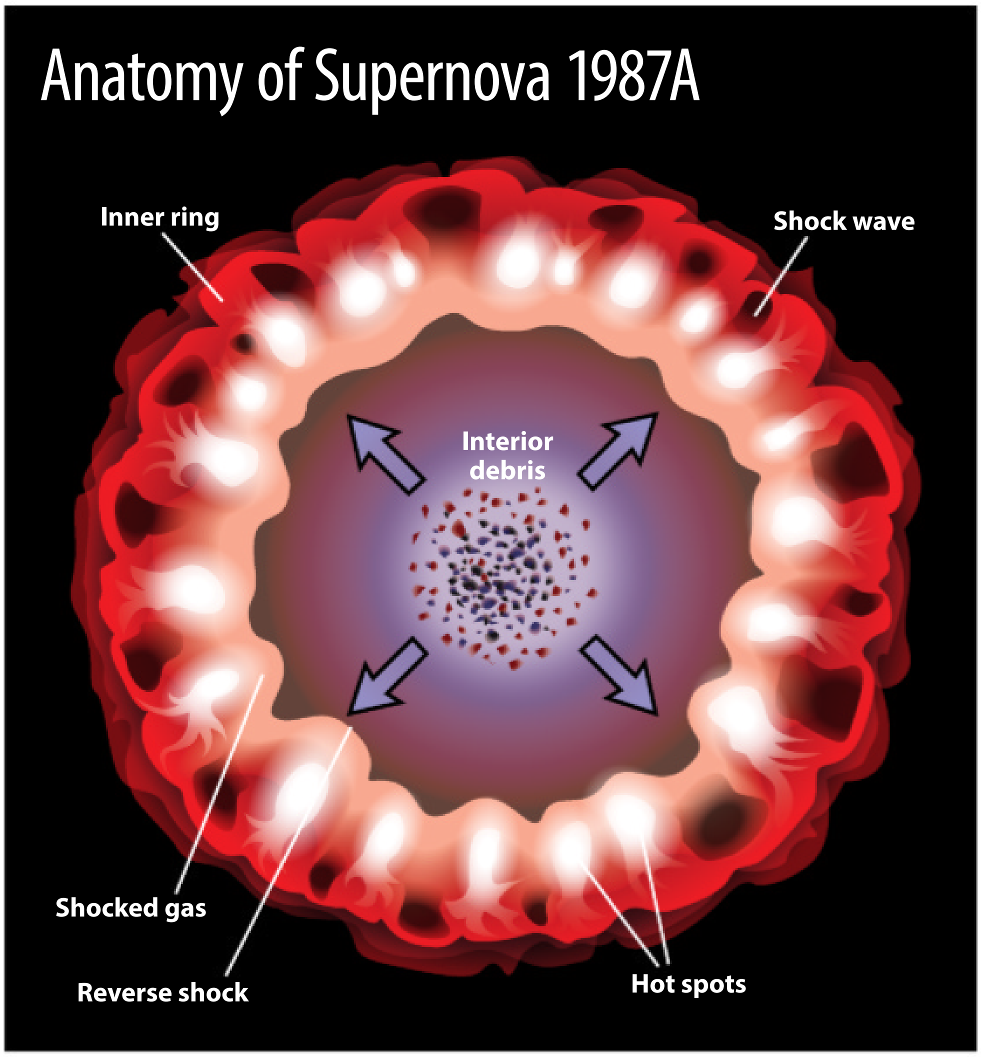
The historic explosion

SN 1987A burst onto the scene February 23, 1987, when it shone as a brilliant new star in the



Supernova 1987A's ring comes alive with hot spots over a 12-year period. The ring, composed of material ejected from the progenitor star some 20,000 years before the blast, lights up as the supernova's shock wave heats knots of dense gas.

NASA/ESA/P. CHALLIS AND R. KIRSHNER (CfA)



This illustration shows SN 1987A's structure from a few years ago to coincide with images of the inner ring looking like pearls on a necklace. The pearls are dense gas pockets excited by the supernova's shock wave, which since has started moving beyond the ring. The shock's collision with the ring created a reverse shock that is now heading back toward the center.

ASTRONOMY: ROEN KELLY

southern sky. Many astronomers at first didn't believe the news of a supernova so close to the Milky Way, thinking that colleagues might be playing some sort of cruel joke. But over the next few days, researchers across the globe scrambled to observe this beacon and confirmed that it lay in the nearby LMC. Its location couldn't have been much better — almost any Milky Way supernova would have been heavily obscured by intervening dust.

By comparing photographs of SN 1987A's region taken before and after the explosion, astronomers soon pinned down which star had detonated. It was a supergiant star cataloged as Sanduleak –69°202 that held the mass of several Suns and burned so hot that its surface appeared blue. At this star's core, just like in all stellar cores, the temperatures and pressures were high enough to fuse atomic nuclei into heavier elements.

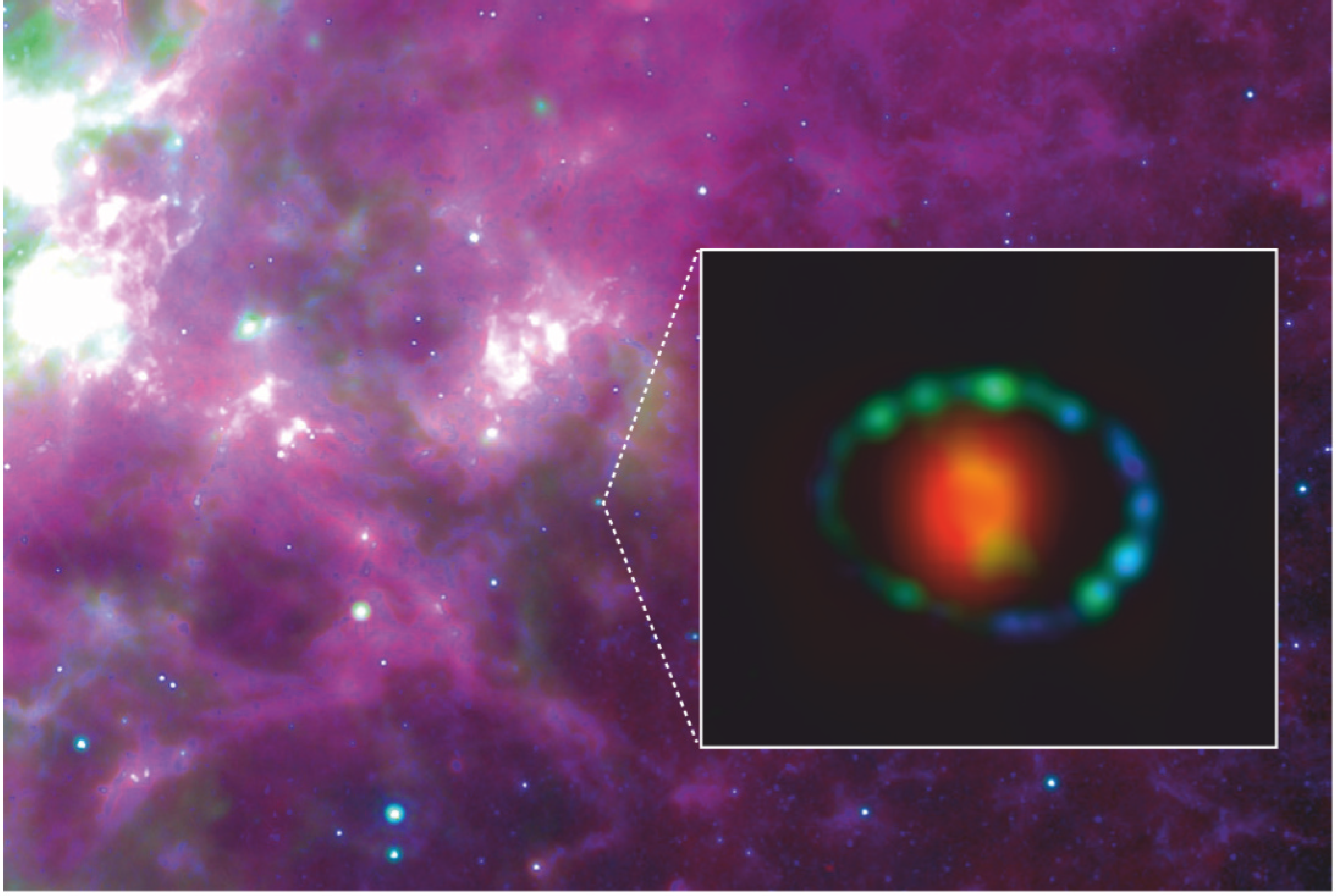
Once the star that led to SN 1987A developed a heart of iron, it could no longer create heavier elements. Its core then began to collapse, and the star's outer layers fell toward the imploding interior. When the core reached the density of an atomic nucleus, it abruptly stiffened and generated a shock wave that blew off the gaseous outer layers. In 2019, astronomers found evidence of the collapsed core, a neutron star that had been missing for over 30 years.

The exploded layers of gas rushed away from the blast site at varying speeds, the fastest moving at about one-tenth the speed of light. For a couple of years afterward, the supernova glowed thanks to radioactive elements created in the explosion that were scattered throughout the debris. These elements decayed naturally, emitting energy in the process that heated the gas. But by 1990, SN 1987A's radioactive elements no longer powered the growing remnant. So, the gaseous leftovers cooled and dimmed.

By 1997, though, SN 1987A's remains had started brightening again — but not because of radioactive materials. Instead, the high-speed gaseous shock front that had rushed away from the explosion site had slammed into surrounding interstellar gas. The collision heated knots in the newfound material. The heated gas, however, wasn't keen on this fresh influx of energy, so it released light in an effort to shed some of the excess. Astronomers first saw this emission, appearing like glowing pearls on a necklace, in wavelengths of optical light in 1997 using the Hubble Space Telescope.

Then, in July 1999, the Chandra X-ray Observatory launched. Three months later, astronomers obtained their first X-ray view of SN 1987A. Roughly every six months since then, Penn State astronomer David Burrows has captured images of the remnant using this telescope. The X-ray emission appears as a ring — Chandra doesn't have the angular resolution to make out the individual "pearls" — of hot gas glowing at roughly 1 million kelvins.

Astronomers now know where this ring of material comes from: Sanduleak –69°202 shed this gas some 20,000 years before the blast. But they don't agree on what process led the star to cast off a few solar masses' worth of star stuff. Either the star was rotating so fast that it launched a dense wind of material from around its equator, or two massive stars merged all those thousands of years ago and flung off the gas. That discarded matter moved more slowly than the explosion's shock front, so when the blast wave hit this preexisting ring, those clumps glowed. The knots brightened in Hubble image



The Spitzer Space Telescope and Herschel Space Observatory show infrared radiation from stars and dust in SN 1987A's vicinity. INSET: ALMA reveals the glow from cold carbon monoxide molecules (red) at the blast site's center, while Hubble captures hot gas in the surrounding ring. ESA/NASA/HERSCHEL/SPITZER/STScI/ESO/ALMA

after Hubble image, starting in 1997 and ending just a few years ago.

Illuminating inside and out

Now it seems as though the blast wave is moving beyond the ring. Swedish astronomers Claes Fransson and Josefin Larsson have led the recent Hubble Space Telescope observations of the ring, and the images show the pearls growing fainter and losing their luster. New clumps of matter outside of the main ring have started to appear. The farther away from the blast site that astronomers look, the further back in time they can see. That means that as the shock front moves into this new region, it's telling scientists about what Sanduleak –69°202 shed before the 20,000-year-old ring of material. "As this shock wave continues to evolve, we'll see more and more of the mass-loss history of the progenitor star," says Larsson.

While Chandra doesn't have the resolution to pick out individual clumps in the X-ray emission, its data also show that the brightness has plateaued. "The shock wave is moving past the ring into something else. And that's exciting because we don't know what's there," says Frank, who works with Burrows on the Chandra data.

The ring's radiation has overwhelmed any less-intense X-ray light from other regions of the remnant. But soon the ring should dim, and Frank and Burrows expect other regions to start becoming visible in X-rays. Specifically, they're looking for material compressed by a secondary front. When the blast wave slammed into the ring's inner edge, most of it passed through and heated the material to ignite the known ring, says Burrows, but part of that shock would have reflected off the ring's inner edge and is now moving back toward the remnant's interior. "That's called the reverse shock," he says.

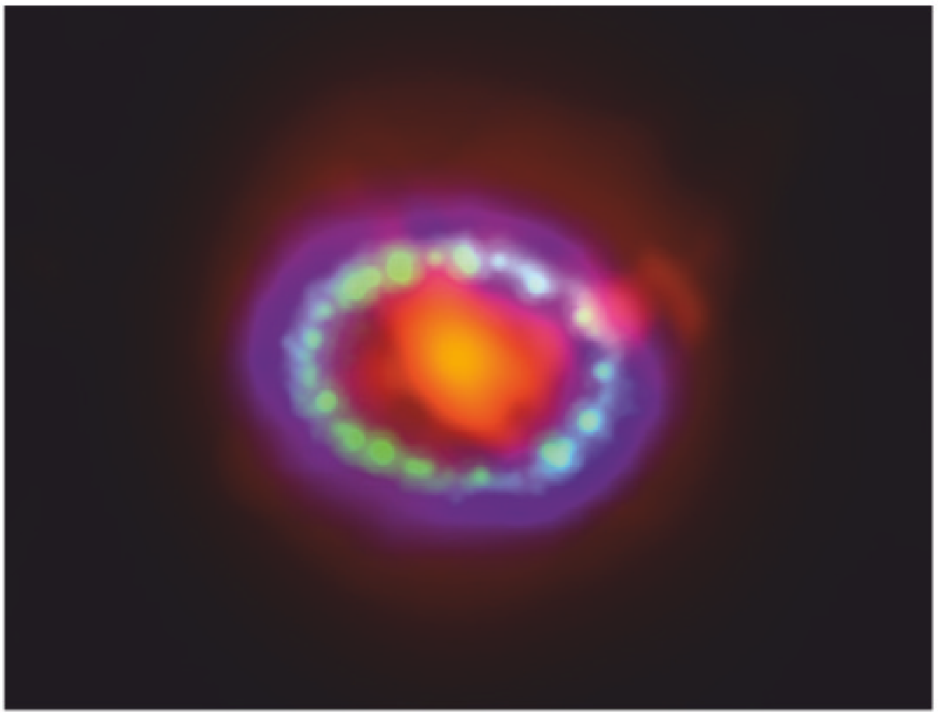
Supercomputer simulations by Salvatore Orlando of Italy's Osservatorio Astronomico di Palermo and colleagues predict the reverse shock should begin encountering the star's exploded debris — the ejecta — in five to seven years.

Cool things down

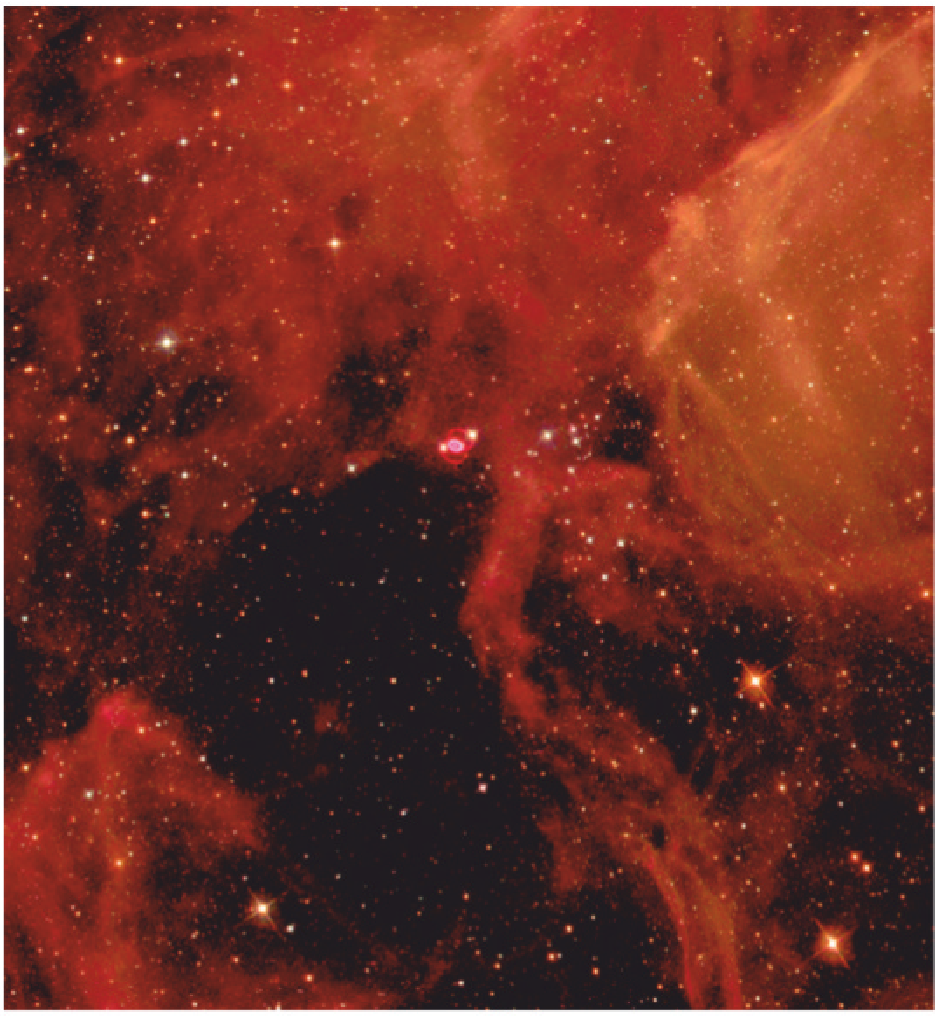
Supernova explosions release an immense amount of energy and drive temperatures sky high. Even today, SN 1987A's ring glows in optical and X-ray light because the blast wave has excited the atoms there to temperatures of a million degrees. With so much of the focus during the past three decades on the ring, it's easy to think that the whole supernova remnant must remain hot. But the ring is the exception — the rest of the remnant is frigid.

At the center of the explosion's site, material has long expanded away, radiating energy and thus heat in the process. In fact, the remnant's center is now cool enough for atoms to have

Because astronomers haven't yet seen a central neutron star in SN 1987A, they can put limits on how bright — or rather, faint — it must be: It's probably 1,000 times fainter than the Crab Nebula's neutron star.



ABOVE: ALMA captured radiation from newly formed cold dust (red) in the interior of the SN 1987A remnant. Visible-light and X-ray emission imaged by Hubble and Chandra, respectively, reveal where the expanding shock wave slams into surrounding gas. R. INDEBETOUW ET AL./A. ANGELICH (NRAO/AUI/NSF); NASA/STScI/CfA/R. KIRSHNER; NASA/CXC/SAO/PSU/D. BURROWS ET AL.



LEFT: A three-ring circus gathers tightly around the site of SN 1987A while wispy tendrils of unrelated gas frame the scene in this composite view from 1994, 1996, and 1997. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

For Mikako Matsuura and her colleagues' next observing project, they are using ALMA to study whether dust and molecules mirror each other in the SN 1987A remnant. Most scientists think they should, but the universe sometimes surprises us.

combined into molecules, and for some of those molecules to have conglomerated into dust particles. The temperatures here range between 20 and 100 kelvins. (Remember that water on Earth freezes at 273 K.) To study material at these cool temperatures, astronomers turn to less-energetic light and the instruments that collect it: infrared telescopes and submillimeter arrays.

The most crucial tool in this work has been the Atacama Large Millimeter/submillimeter Array (ALMA) in northern Chile. ALMA can separate details just 0.05" from one another on the sky, which is better resolution than even what Hubble can achieve. To study SN 1987A's dust, which radiates at these cold temperatures, Mikako Matsuura (then at University College London) and her colleagues combined 2013 observations using a still-incomplete ALMA with 2012 infrared data from the European Space Agency's Herschel Space Observatory. They found that the remnant houses an enormous amount of dust — about one-half of the Sun's mass.

The dust that astronomers talk about isn't like the dust that whips around after you drive along a dirt road. Instead, it's similar to the texture of smoke. Cosmic dust can range in size from a few molecules up to 0.1 millimeter across, and it radiates at temperatures of only about 20 kelvins.

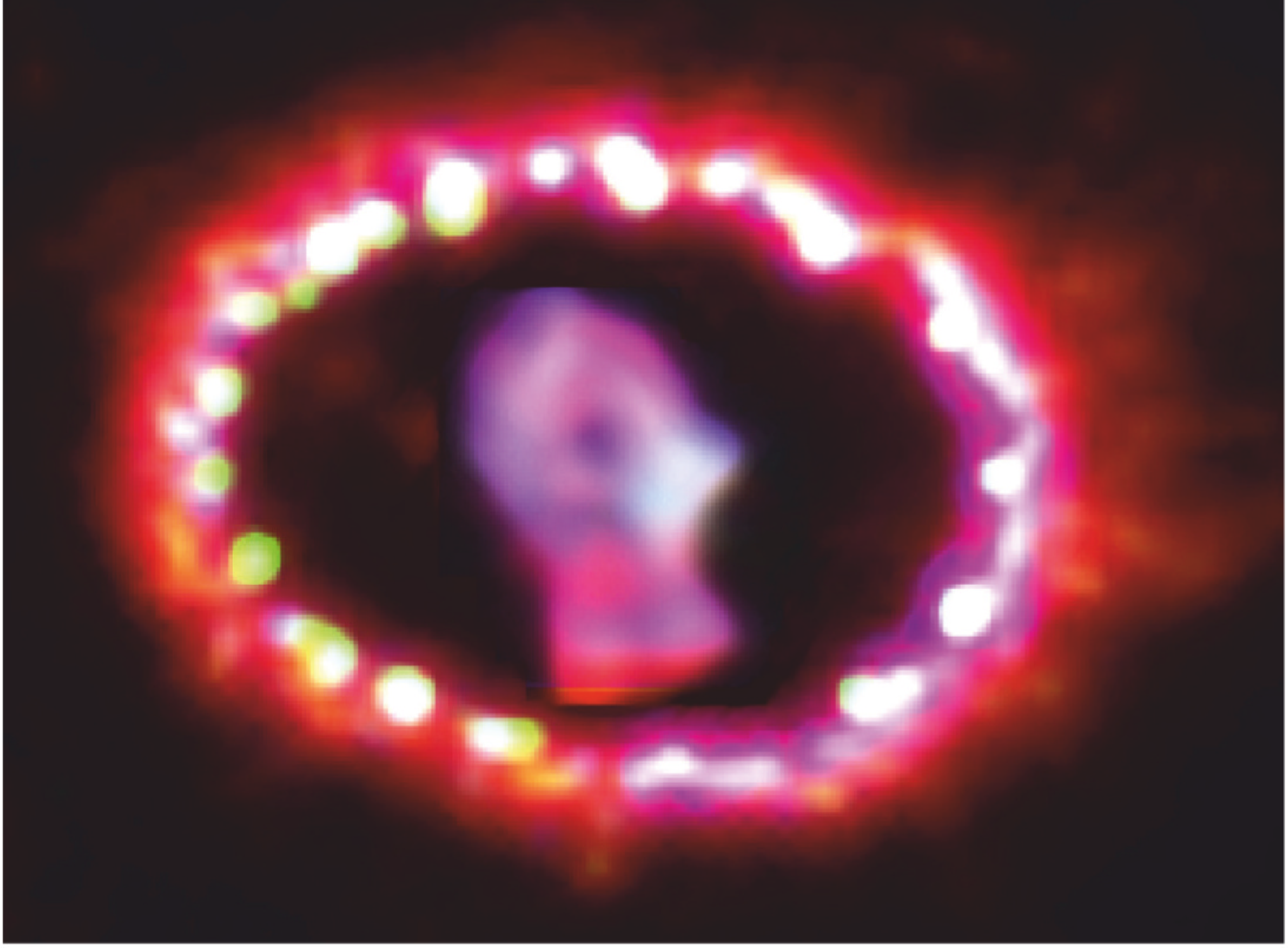
Because astronomers can't put the dust lurking in SN 1987A's center on a scale to weigh it, Matsuura's team turned to the same tool scientists have used for decades: the collected light. They knew the material's temperature from the type of light it emitted (submillimeter and far-infrared), and they knew that a brighter signal equated to more material. "So the total brightness from the object can give the total mass," says Matsuura. "It's simple physics." What isn't so simple, however, is understanding the process that creates all that dust — or what processes could destroy it.

Mapping the star's guts

The same group of astronomers also is using ALMA and infrared instruments to observe molecules in the remnant's ejecta. Whereas studying dust gives scientists limited information, such as what type of object can create the tiny particles, molecules give more insight into the physics of what's going on. Each type of molecule is made up of a unique combination of elements and emits light of specific colors, or wavelengths. This means that astronomers can figure out what molecule they're detecting by measuring the wavelengths of light their instruments see. And they can gather an array of additional information from the detected molecules: the direction and speed of motion (toward and away from the telescope), temperature (because certain molecules exist only at certain temperatures), and the amount of the molecule. With all these details, they can begin to piece together information about the exploded star's innards.

However, it isn't only cold molecules that astronomers can use to peer inside the ancient progenitor star.

A specific wavelength of high-energy X-ray radiation traces a radioactive element that scientists know must have been produced in the supernova blast. Using data collected by NASA's



SN 1987A has now evolved into a supernova remnant. The proof came in this 2011 Hubble image showing a fish-shaped central structure of expanding supernova debris. This material has started to brighten as it basks in the X-ray glow from the surrounding ring of pre-supernova material. NASA/ESA/P. CHALLIS (CfA)

NuSTAR X-ray observatory between 2012 and 2014, researchers studied the distribution of titanium-44. How this element is scattered across the remnant can reveal how turbulent the motions inside the progenitor star were during the blast. And it also can show how asymmetrical the explosion was. It turns out that SN 1987A was very lopsided.

Larsson, in addition to her Hubble studies of the optical pearl necklace, also has worked on mapping the motions of different elements and molecules in the remnant. She's used Hubble and the Very Large Telescope in Chile to get at these values with a goal of teasing out ever more details of the explosion from its ejecta.

Specifically, Larsson is measuring each gas cloud's movement toward or away from Earth, and from that value she can calculate how far away it lies. "We'll build up a more detailed view of the three-dimensional distribution of different elements and molecules," she says. Combining these data with the molecular information from ALMA observations will lead, she says, to a detailed 3-D map of the explosion. So far, Larsson and her colleagues have mapped hydrogen, iron, silicon, calcium, magnesium, and oxygen — and these elements are not distributed symmetrically.

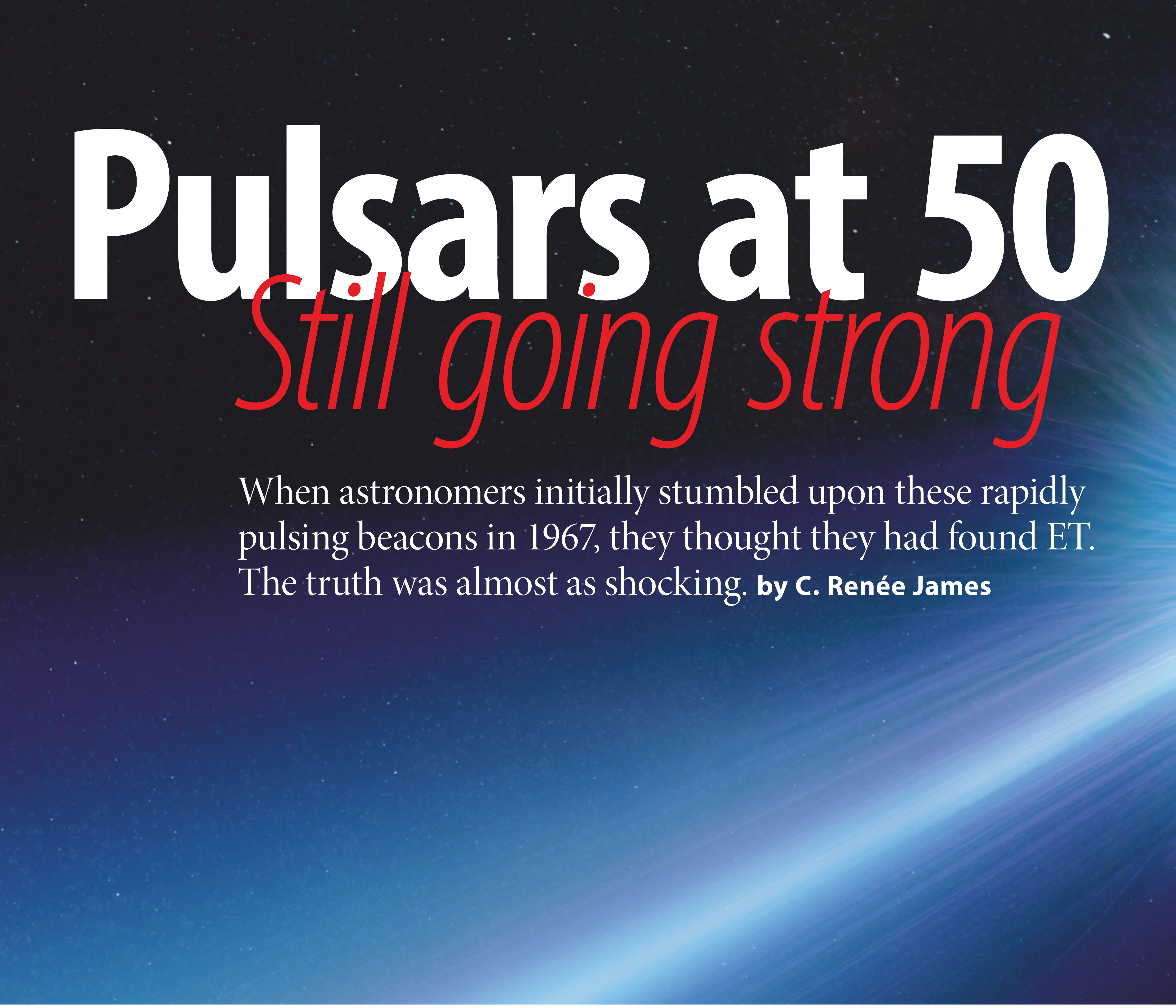
With multiple pieces of evidence showing that the SN 1987A blast was asymmetric, perhaps astronomers will be able to find out more about how the explosion happened. Most computer models fail to produce supernovae — they stall out during the blast and can't explode the star. But supernovae occur across the cosmos and spew their ejecta into the interstellar environment. SN 1987A and its resulting remnant make for the best constraints that scientists have to compare computer models against.

Astronomers have big goals for their studies of SN 1987A and its remnant, and they'll need to continue observing the blast site to reach those goals. It's a rare opportunity to watch in detail as a cosmic object evolves, and scientists aren't taking this next-door explosion for granted. Until the universe provides us with another nearby supernova to study with modern tools, SN 1987A will remain the best target. "We need to watch it while we can," says Frank. "It may be our only chance for a long time."

Although **Liz Kruesi** *was alive for SN 1987A's February 1987 appearance, she wasn't yet old enough for her interest in astronomy to have kicked in.*

DEFINING THE TRANSITION

Even though we still call the object "Supernova" 1987A, most astronomers accept that this is a remnant now, and not a supernova. The phrasing is important, and it relates to a crucial transition period that scientists don't know much about. That's because the transition isn't something they can test in a laboratory or see anywhere else in the sky. They need to make out the structural details of a supernova evolving into a remnant — and that's possible only with SN 1987A. *— L.K.*



Pulsars at 50

Still going strong

When astronomers initially stumbled upon these rapidly pulsing beacons in 1967, they thought they had found ET. The truth was almost as shocking. **by C. Renée James**

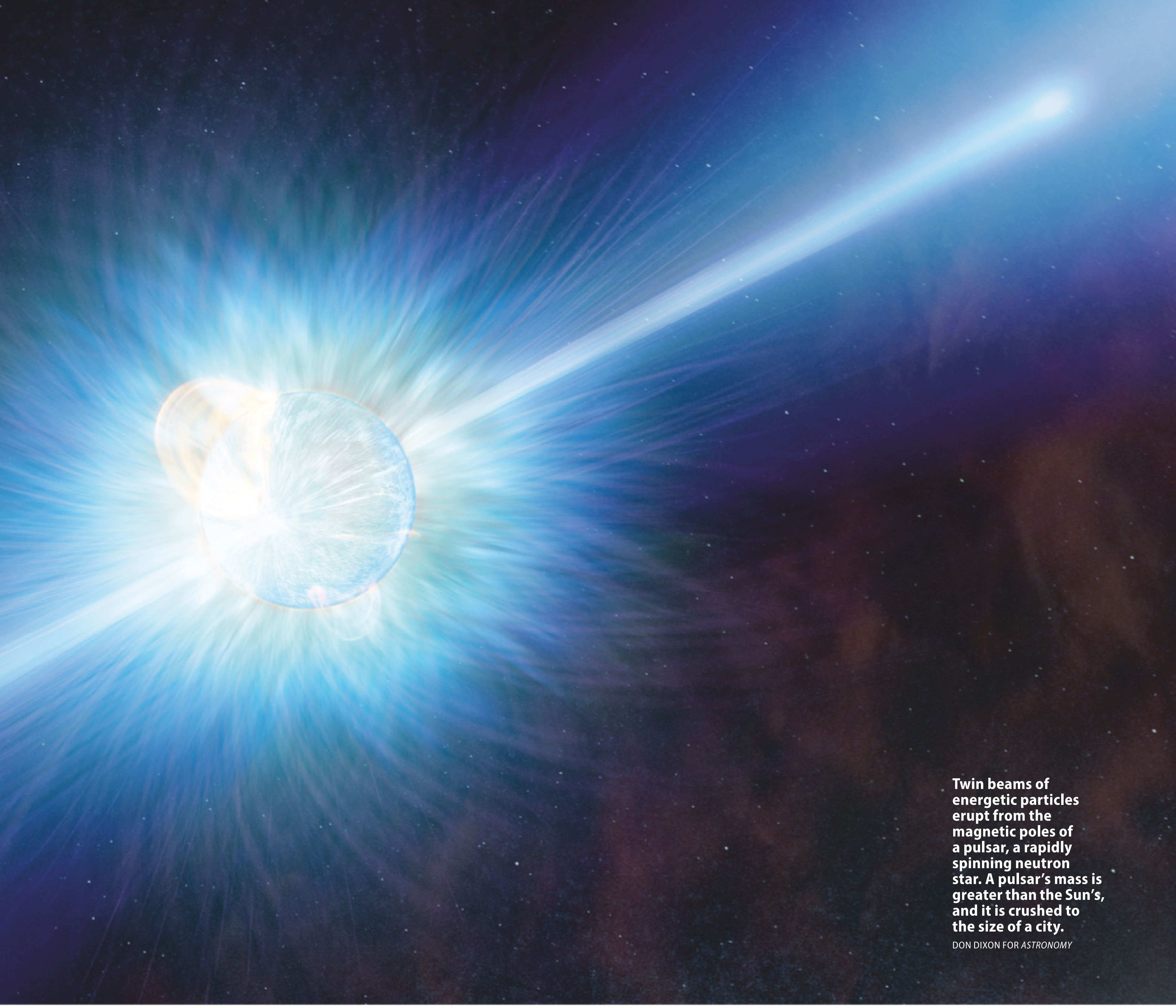
A little more than 50 years ago, an unassuming bit of "scruff" appeared in Jocelyn Bell Burnell's radio telescope data. Although barely noticeable at first, the scruff quickly led to two Nobel Prizes, provided evidence that Albert Einstein's general relativity was right, rode on humanity's first interstellar vehicle, and became the inspiration for a watch, a car, and an album cover.

The objects revealed by the scruff — dubbed "pulsars" — turned out to be smaller than a city but more powerful than the Sun. And if everything goes right, they soon will help us detect the most colossal events in the cosmos and even help us navigate to the stars.

Despite its meteoric rise to fame, the pulsar had an unpromising start. In July 1967, Bell Burnell noticed a quarter-inch-wide radio signal barely rising above the background noise on the recordings. It would have been easy for anyone else to ignore, but Bell Burnell had almost single-handedly strung 120 miles (193 kilometers) of wire to create the 4.5-acre radio telescope at Mullard Radio Astronomy Observatory near Cambridge, England, making her fast friends with everything it had ever picked up. She was not about to let anything escape her attention, no matter how scruffy.

Fortunately, the scruff showed up more than once. In fact, as she pored over the miles of charts, the keen-eyed graduate student spotted the signal on about 10 percent of the printouts, arriving four minutes earlier each day. Keeping time with the stars, the source definitely was not terrestrial. But what was it?

She persuaded her Ph.D. adviser, Antony Hewish, to speed up the paper feed so she could better scrutinize



Twin beams of energetic particles erupt from the magnetic poles of a pulsar, a rapidly spinning neutron star. A pulsar's mass is greater than the Sun's, and it is crushed to the size of a city.

DON DIXON FOR *ASTRONOMY*

the odd signals. For weeks, miles of charts streamed through. As the piles of paper grew, so did Hewish's frustration. Finally, on November 28, 1967, as they were about to pull the plug on the search, the signal returned.

Now, instead of a bit of scribbly fuzz, a series of regularly spaced shallow bumps appeared, each separated from its neighbors by 1.3373 seconds. These precisely timed, rapid radio blips telegraphed information about uncharted astrophysical territory. Because known stars could not change brightness so rapidly, the scientists knew they were looking at an unfathomably dense, small object. Or — did they dare suggest — could it be something artificial?

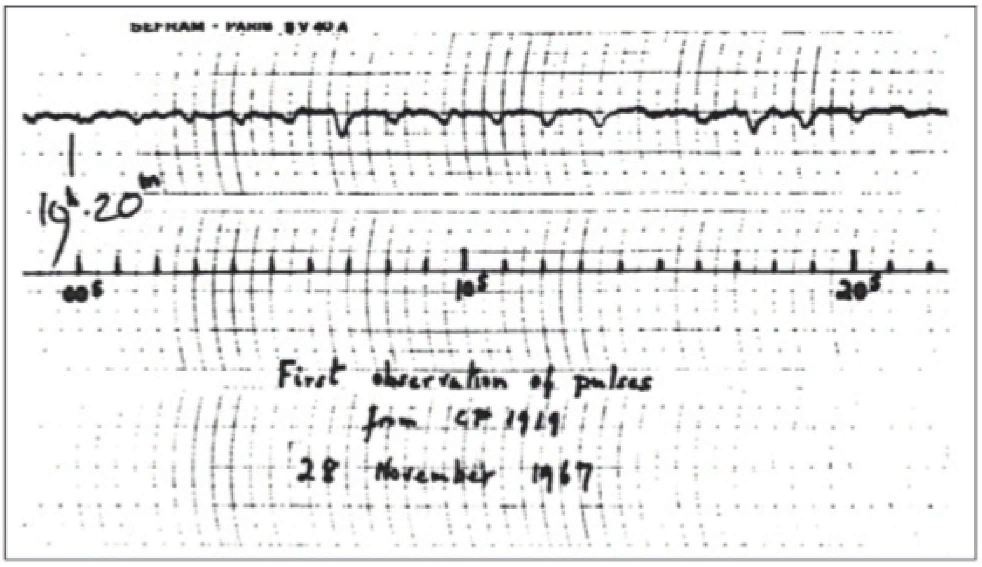
LGM or not?

Although Bell Burnell and Hewish agreed that the latter explanation was highly unlikely, unusual signals are a siren song to astronomers. Despite healthy skepticism, most people are open to the possibility that someone, or something, in this vast universe might try to make contact. And so Bell Burnell gave the object the tongue-in-cheek nickname "LGM-1," for "Little Green Men."

The next step was to look for Doppler shifts, telltale changes in the signal's wavelength that let astronomers know an emitting object's comings and goings. These new data would let them know if the signal had been broadcast from a planet orbiting a star. Before that investigation even got off the ground, however, another similarly regular signal joined LGM-1. Then another. And another.

At that point, Bell Burnell recalls, they gave up on the idea of aliens. "It was extremely unlikely that there would be four separate lots of Little Green Men, all, at

Jocelyn Bell Burnell appears in front of one of the large radio telescopes at Cambridge University's Mullard Radio Astronomy Observatory in 1968. CAMBRIDGE UNIVERSITY



ABOVE: This bit of "scruff" — the slight dips seen in the top row of data — represents Jocelyn Bell Burnell's initial detection of pulses from the pulsar CP 1919+21 (now known as PSR B1919+21) from November 1967. CAMBRIDGE UNIVERSITY

LEFT: Burnell stands among the more than 1,000 posts and 120 miles (193 km) of wire and cable that formed the radio telescope she used to discover pulsars in the late 1960s. CAMBRIDGE UNIVERSITY

the same time, signaling to the inconspicuous planet Earth using a stupid frequency and a daft technique," she said.

Although the signal proved not to be an extraterrestrial greeting, it was a tremendous astronomical discovery in its own right. The researchers soon found out that whatever it was, it kept time to better than 1 part in 10 million, either rotating or pulsating (they weren't sure which) more than 60,000 times per day. On top of this, it was emitting enough power across interstellar distances to be detected even by 1967 instruments.

The neutron star connection

This sort of activity required a phenomenal source of energy. Astronomers Fritz Zwicky and Walter Baade hinted at one back in 1934, when they hypothesized that an exploding massive star — they called it a "supernova" — might leave behind a dense core composed mainly of neutrons.

It was a wild idea with seemingly little chance of verification. How would anyone ever detect a city-sized ball of neutrons, even one at a temperature of a million degrees? For the most part, astronomers ignored Zwicky and Baade's prescient paper and quietly assumed that massive stars died by blowing themselves to smithereens.

Then came LGM-1, which soon became CP 1919+21 and ultimately PSR B1919+21. If the object were physically pulsing, growing and shrinking, Bell Burnell and Hewish computed a density equivalent to a mountain squeezed into a thimble: 10 trillion grams per cubic centimeter, the same density as a ball of neutrons.

Since it was a pulsating signal from a stellar source, science journalist Anthony Michaelis christened the object a "pulsar" in 1968. Although scientists were still several months from understanding whether the object was pulsating or rotating, the moniker stuck.

It was admittedly a catchy name. Less than three years after Bell Burnell's discovery, the Hamilton Watch Co. began developing the Pulsar watch, capitalizing on nature's seemingly perfect timekeepers. The first Nissan Pulsar, which was — what else? — a compact car, rolled off the assembly line in 1978.

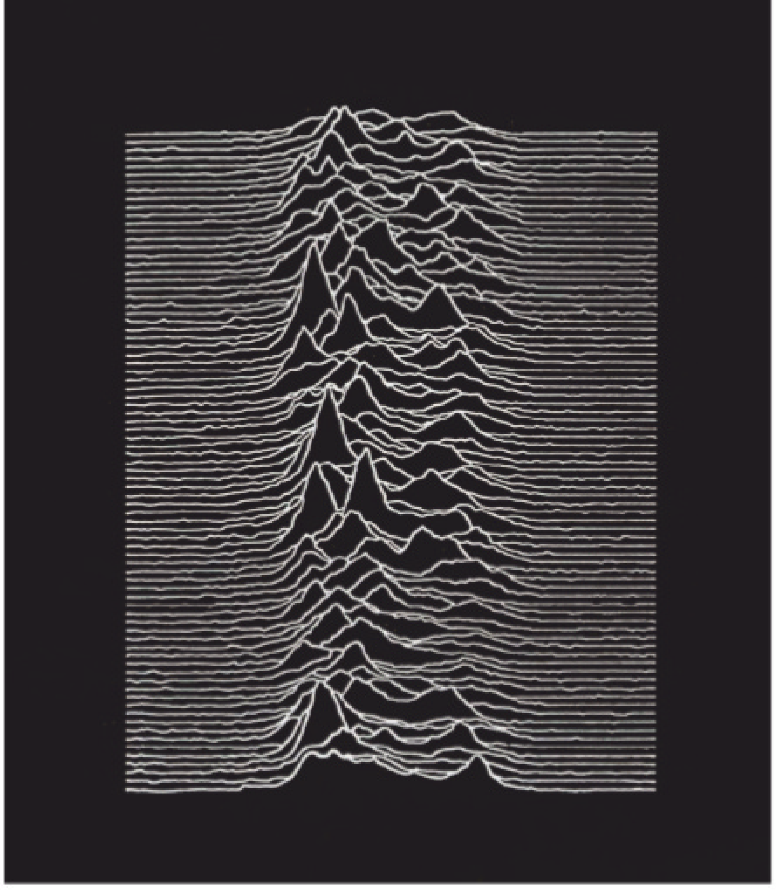
In 1979, pulsars slipped effortlessly and largely unrecognized into popular culture. Next to the entry in the 1977 edition of *The Cambridge Encyclopedia of Astronomy* was an image of successive stacked pulse profiles from PSR B1919+21. The simple but enigmatic portrait of squiggles might have remained in that

AN EARLY WARNING OF PULSARS

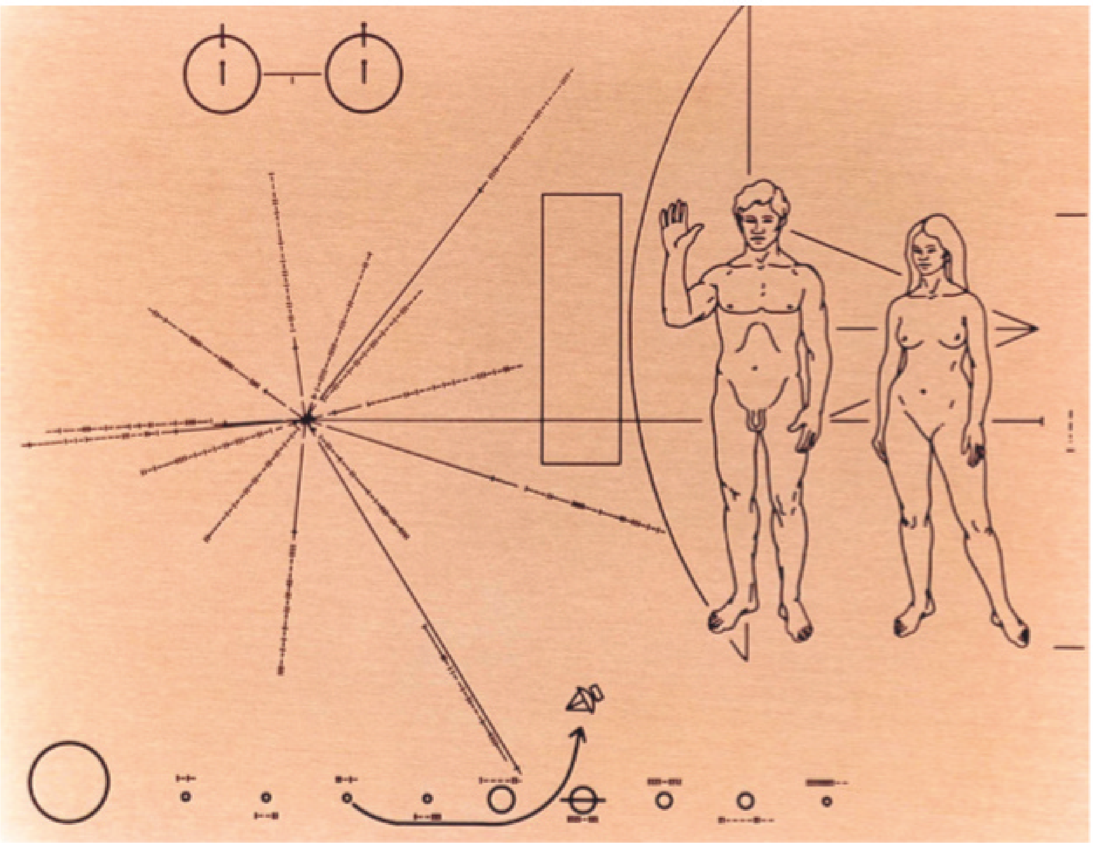
U.S. Air Force Staff Sgt. Charles Schisler knew something was odd in the radar signals he was monitoring. It was summer 1967, and the signal had been showing up for weeks, keeping time with the stars by rising four minutes earlier each night.

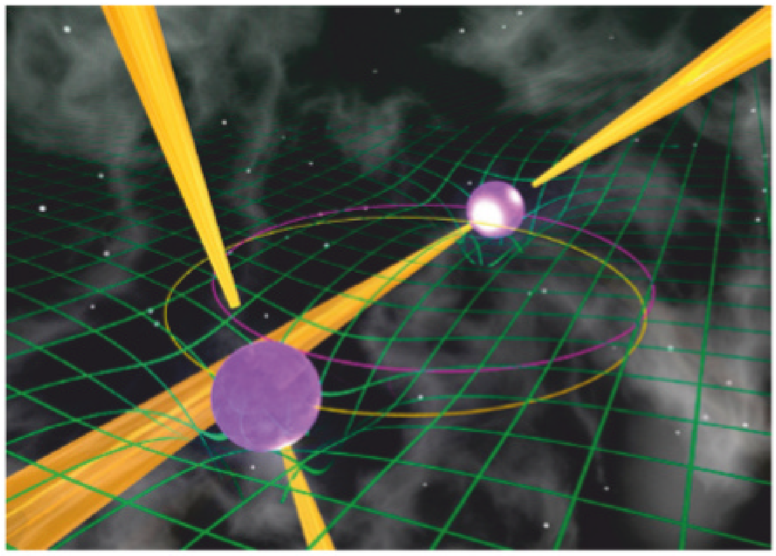
Unfortunately, his employer wasn't at all interested in this sort of signal. The Ballistic Missile Early Warning System at Clear Air Force Station in Alaska was built to detect incoming warheads, not pulsars. As a result, Schisler wasn't at liberty to announce his discovery or do any formal follow-up observations.

It wasn't until 40 years later that information from the Early Warning System became declassified, and Schisler felt comfortable revealing that he had observed not just one pulsar, but a dozen or so. Even then, Schisler was quick to point out that his detections never hinted at the pulsing nature of these sources, a key to understanding the objects responsible for the signals. That honor still goes to Jocelyn Bell Burnell. —*C.R.J.*



These enigmatic squiggles represent pulses from CP 1919+21 recorded with the Arecibo radio telescope. Harold Craft Jr. created this visualization for his doctoral thesis. It became a part of pop culture when Joy Division used it on the cover of the band's debut album, *Unknown Pleasures*. HAROLD D. CRAFT JR.





TOP: The Pioneer 10 and 11 spacecraft each carried a plaque describing the Sun's location for any extraterrestrial intelligence that might find the probe. Carl Sagan and Frank Drake used the positions and periods of 14 pulsars (the lines emanating from the star left of center; the horizontal 15th line gives the direction to the Milky Way's center) to mark the spot. NASA

ABOVE LEFT: PSR J0737–3039 is the only known double pulsar, a binary system in which both objects are pulsars. The two orbit each other once every 2.45 hours. Scientists are using the pair, illustrated here along with the underlying fabric of space-time, to test Einstein's theory of general relativity. MPIfR/M. KRAMER

encyclopedia and in obscure journal articles if it hadn't caught the eye of Peter Saville, who decided that it would make the perfect cover art for Joy Division's 1979 album *Unknown Pleasures*. These days, plenty of people recognize the image that's been featured on everything from T-shirts to tattoos, but few realize it represents the first pulsar discovered.

So what exactly are these objects that have captured the attention of astronomers, watchmakers, car companies, and album art designers? The simplest description is that they are rapidly rotating, highly magnetized, city-sized, collapsed cores of dead, high-mass stars — the neutron stars Zwicky and Baade proposed.

But this portrayal utterly fails to convey the bizarre and extreme character of a pulsar. Nature crams up to three times the mass of the Sun into its tiny volume, making its surface gravity second only to that of a black hole. Its magnetic field strength can be a quadrillion times Earth's, far exceeding anything scientists can create in a laboratory.

This mega-magnetism whips up charged particles in the vicinity, causing them to swarm around the magnetic poles and emit beams of intense radiation. These beams become a sort of lighthouse beacon, sweeping across the universe as the neutron star spins. On the off chance that Earth happens to lie in the beam's path, we see a quick blip with every rotation.

Pulsars are laboratories of extreme physics, and their discovery opened up an entirely new field. The find was so significant that just seven years later, Hewish would share the Nobel Prize in Physics "for his decisive role in the discovery of pulsars." The exclusion of Bell Burnell, who treated even the smallest, most unusual bit of data as significant, has been hotly debated ever since.

Astronomers estimate that up to a billion massive-star remnants should exist in the Milky Way, but only a million or so are pulsars. So far, only about 2,300 have turned up. Pulsars aren't permanent, after all. As the rotation, magnetic field, and local supply of electrons peter out over a few million years, so does the lighthouse beam. During a human lifetime, however, a pulsar's timing is typically as precise as an atomic clock's, changing by about a billionth of a second per year.

The presence of a stellar companion, though, can wind them up and turn them into even better timing devices. In 1982, astronomers discovered the first millisecond pulsars, objects whirling around at more than 100 times per second. The current record belongs to PSR J1748–2446ad, which rotates 716 times per second. Not merely curiosities, these speed demons may help future astronauts find their way.

Toward a pulsar GPS

Astronomers hatched the idea to use pulsars as navigation tools on the heels of their discovery, but in 1972, it literally was etched in gold. As scientists were putting the finishing touches on the Pioneer 10 spacecraft for its journey through the solar system and beyond, they wondered if they could convey the craft's "home" to any extraterrestrials it might come across. If only there were some way to indicate our position relative to

A pulsar spinning 30 times per second powers the emission from the Crab Nebula supernova remnant (M1). The pulsar is the bright dot in the heart of the central, hollowed-out region. This composite image shows visible light as red and X-ray radiation as blue.

NASA/HST/CXC/ASU/J. HESTER ET AL.

objects with precisely known properties, like a sort of galactic GPS.

"Pulsars are the obvious answer," Carl Sagan declared. And with just three weeks left to design and etch the gold plaque that would ultimately be affixed to Pioneer 10 and its twin, Pioneer 11, he and Frank Drake created a map of the Sun relative to 14 pulsars. They also included a code indicating universal constants that intelligent aliens should be able to decipher. With the map and the spin-down rate of each pulsar, extraterrestrials would know not only where we are, but also when we launched the probe.

Maybe. "The data for one pulsar on the plaque is wrong, and so the aliens would need to sort that out!" jokes pulsar researcher George Hobbs at Australia's Commonwealth Scientific and Industrial Research Organisation.

What about us? Could we ever use pulsar GPS as we leave the safety of Earth? Our current GPS, which uses Earth-orbiting satellites, obviously wouldn't help us navigate to Mars, much less to other star systems. Looking to the future, Hobbs and his colleagues have explored the feasibility of using pulsars as navigation tools.

The idea is straightforward in principle. On Earth, we know when to expect pulses from pulsars. And because light takes time to travel, those arrival times depend on our exact location. Complicating matters is the fact that pulsars, well, pulse — frequently. The universe hosts an infinite number of places where you can expect a pulse from a given pulsar at a particular time, but by observing several pulsars, you can quickly narrow the set of places you might be.

It takes a bit of computational gymnastics to settle on the right one, but Hobbs and his colleague Xiaopeng You have performed those acrobatics with data from millisecond pulsars and successfully pinpointed the location of the 64-meter Parkes radio telescope in Australia to within 0.6 mile (1 km). They even confirmed that Earth revolves around the Sun, just in case anyone was still on the fence about that.

"The main challenge is being able to detect pulsars without a huge telescope," says Hobbs. "Of course, you're not going to launch the Parkes telescope into space!"

Even if you did, it wouldn't be of much use. A single radio dish can observe only one pulsar at a time, but, as is the case with terrestrial GPS, you need simultaneous information from several different clocks. A single X-ray telescope might do the trick, however, and several teams around the globe have jumped on the X-ray pulsar navigation bandwagon.

"The Europeans seem to have a crazy package to see if they can navigate aircraft [with pulsars]," says Hobbs. "And the Americans and Chinese are both undergoing research into deep-space navigation with pulsars."

A time for pulsars

Pulsar timing should prove useful for more than navigation. When he's not wrestling with issues of pulsar GPS, Hobbs and others are looking to these neutron stars to help us listen in on the most gargantuan cosmic events.

We can thank Einstein for the idea that our universe is an interwoven tapestry of matter, space, and time. According to his theory of general relativity, when matter moves, the rest of the tapestry ripples predictably in response. On September 14, 2015, the Laser Interferometry Gravitational-wave Observatory (LIGO) directly detected gravitational waves for the first time. Two black holes, each about 30 times the mass of the Sun, collided over a billion years ago, causing space to literally (and measurably) contract and expand.

But many people aren't aware that pulsars have been whispering rumors about gravitational waves for decades, giving astronomers confidence that they would ultimately detect them directly. In 1974, Russell Hulse and Joseph Taylor Jr. at the University of Massachusetts, Amherst, announced the discovery of a pulsar in orbit around another non-pulsing neutron star. It was the first of its kind: two extreme objects locked in a frantic dance, whirling around each other every 7.75 hours. The system pulls relentlessly at the fabric of the universe, which, in turn, saps energy from the pair. The lost energy spreads into the universe as gravitational waves.

The scenario might sound vaguely familiar. This binary pulsar — PSR B1913+16 — is performing a small-scale version of the tarantella executed by LIGO's famed colliding black holes. Long-term observations show that PSR B1913+16's orbit is shrinking by about 3.2 millimeters per circuit, with the two neutron stars scheduled to collide in just 300 million years. The

THE PULSAR HOUND OF PARKES

Although it was up and running by 1961, the 64-meter Parkes radio telescope in New South Wales, Australia, was not the first to find evidence of pulsars, or even ferret out the first millisecond pulsar. In fact, the radio scope, nicknamed "The Dish," came quite late to the pulsar game.

The telescope — one of the antennas that received the Apollo 11 TV transmissions from the Moon — amassed just eight pulsar discoveries by 1973 and added only about 300 more over the next quarter-century. But once scientists installed a new receiver in 1997 that provided much wider sky coverage, The Dish leapt into action. It would detect more than 100 pulsars per year for the next seven years, outpacing all other radio observatories put together.

The Dish's most significant discovery arguably came in 2004, when it revealed a double pulsar system. A step beyond Hulse and Taylor's pulsar-neutron star binary, the double pulsar allows astronomers to probe Einstein's general relativity further while exploring an eclipsing pulsar system.

All told, The Dish has discovered about two-thirds of the 2,300 or so known pulsars. In addition, it plays a leading role in the International Pulsar Timing Array, the development of pulsar GPS, and bringing pulsar science to a new generation through PULSE@Parkes, an educational program for high school students. —*C.R.J.*

The 64-meter Parkes radio telescope — aka "The Dish" — has discovered about two-thirds of our galaxy's known pulsars. CSIRO

system provides researchers with an extreme gravitational laboratory, one for which Hulse and Taylor received the 1993 Nobel Prize in physics.

Pulsars probe gravitational waves

Pulsars can do more than merely insinuate the existence of gravitational waves, however. Because rotating neutron stars make exquisite clocks, they can be the endpoints of a galactic LIGO setup. LIGO detects passing gravitational waves by measuring how they compress and stretch the instrument's arms. These waves should do the same to the space between pulsars and Earth. Astronomers would then measure subtle variations in the pulse periods, and those changes would depend on the pulsar's direction. LIGO has only four observational arms: two in Livingston, Louisiana, and two in Hanford, Washington. With pulsars, astronomers can have as many observational arms as there are observed pulsars.

It's an elegant and simple plan, one that officially got underway more than a decade ago with the creation of the International Pulsar Timing Array (IPTA). But IPTA is after much bigger quarry than the stellar-mass black hole mergers seen by LIGO. It's trying to listen in on collisions of supermassive black holes. Paradoxically, this task is even more challenging than detecting the mergers of star-sized black holes.

Paul Lasky, a member of both gravitational wave teams, explains the process: "When two galaxies collide, the black holes in their cores will eventually sink to the center of the merged galaxy, and those two black holes will eventually merge themselves." It would seem that the sheer magnitude of such an event would make it easy to detect, but the resulting gravitational waves would have a phenomenally low frequency.

"The period of the waves is approximately one to 10 years," says Lasky. "This means that you need to observe for that amount of time to actually detect a single period." So even with a decade of observing under their belts, astronomers aren't too concerned that IPTA has yet to detect a merger of supermassive black holes.

There is one puzzling gap in IPTA's results, however. If you throw a large rock into a perfectly calm pond, you will see symmetric ripples radiate from the entry point. But the universe has thrown lots of rocks of varying sizes into the cosmic fabric over billions of years, and that should create a jumble of interacting ripples, or what scientists call the stochastic background. "The fact that we have not seen this stochastic background in more than a decade of observations is slightly at odds with theoretical predictions," says Lasky.

Still, with the resounding success of LIGO, gravitational wave scientists now can look more deeply into phenomena that until recently were on the fringe of observational astronomy, just as pulsars were a half-century ago. And there is every reason to believe that in the next 50 years, pulsars will continue to play a starring role in our understanding of the universe.

Not bad for a bit of scruff.

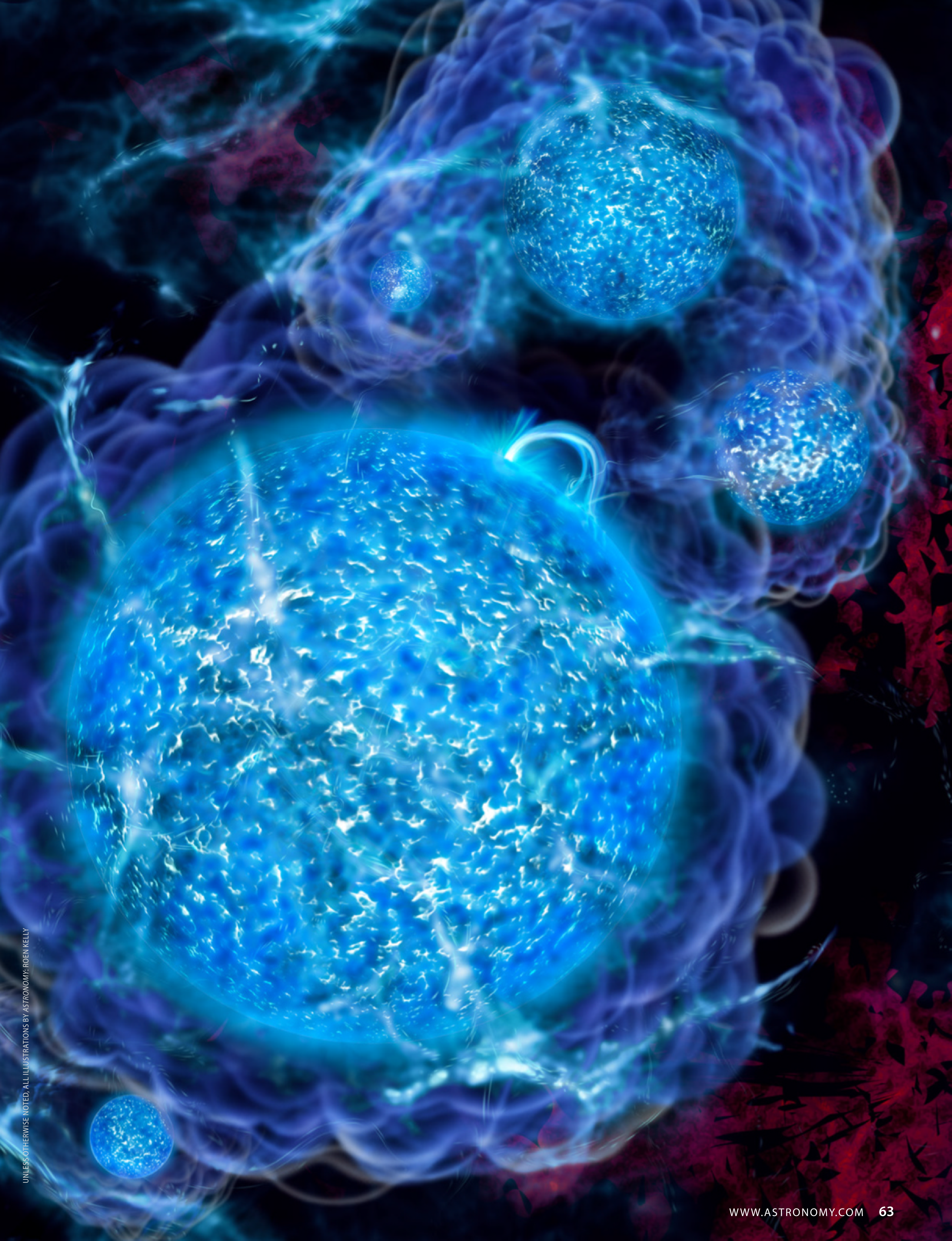
C. Renée James *is a science writer and physics professor at Sam Houston State University in Huntsville, Texas. Her latest book is* Science Unshackled: How Obscure, Abstract, Seemingly Useless Scientific Research Turned Out to Be the Basis for Modern Life *(Johns Hopkins University Press, 2014).*

Dark stars

COME INTO THE LIGHT

With help from dark matter annihilation, some of the universe's earliest stars were able to grow much larger than they would otherwise.

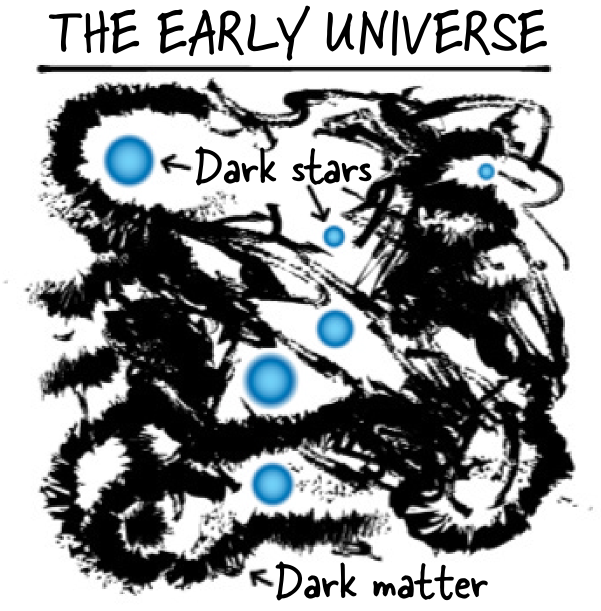
by Mara Johnson-Groh



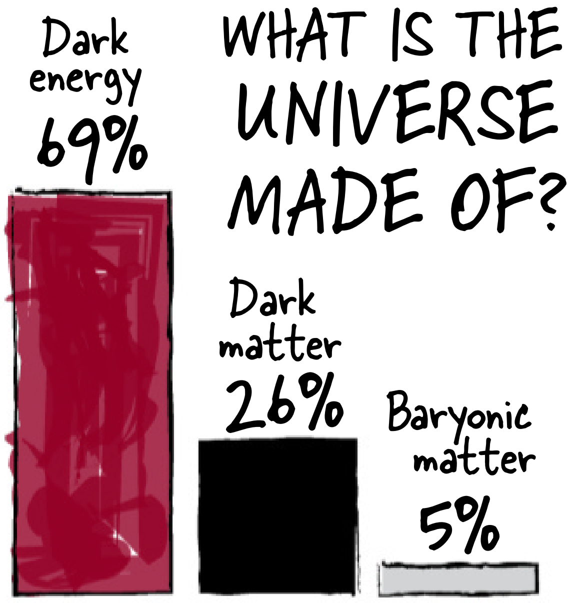
UNLESS OTHERWISE NOTED, ALL ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

LONG, LONG AGO,

the universe looked very different than it does today. When the Big Bang was a recent memory and the first stars were forming and beginning to shine, the universe was much smaller. In this dense environment, a mysterious substance known as dark matter ran amok in infant galaxies. Scientists think that out of this rich environment, a new breed of star was born: dark stars.



Dark stars are somewhat of a misnomer — they're not actually dark. In fact, they're likely some of the biggest and brightest stars in our universe. Yet no one has ever seen one. These giants, powered differently than the stars we see in the night sky, may reveal a lot about the true nature of our universe — that is, if scientists can ever actually find a dark star.



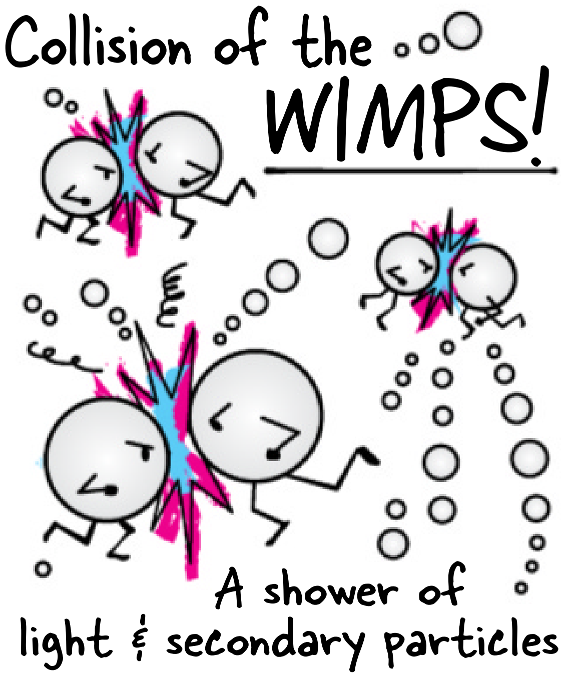
Back to the beginning

Everything we see in the universe today makes up only 5 percent of what is known to be out there. The majority, about 69 percent, is dark energy — the unknown driver that scientists believe is causing the accelerating expansion of the universe. Dark energy doesn't seem to interact with the normal type of matter our world is composed of, called baryonic matter — even gravitationally.

The remaining 26 percent of the universe is dark matter. According to some predictions, hundreds of these dark matter particles zip through your body every second. Fortunately for us, this type of matter, though it follows the laws of gravity, does not interact with the baryons our bodies are composed of. Unfortunately for researchers, this makes it extremely difficult to study. Dark matter emits no light, so it can only be probed indirectly through its gravitational fingerprints, such as the way it bends light around massive galaxies. For the most part, researchers must rely heavily on models to make informed predictions about the nature of this elusive material.

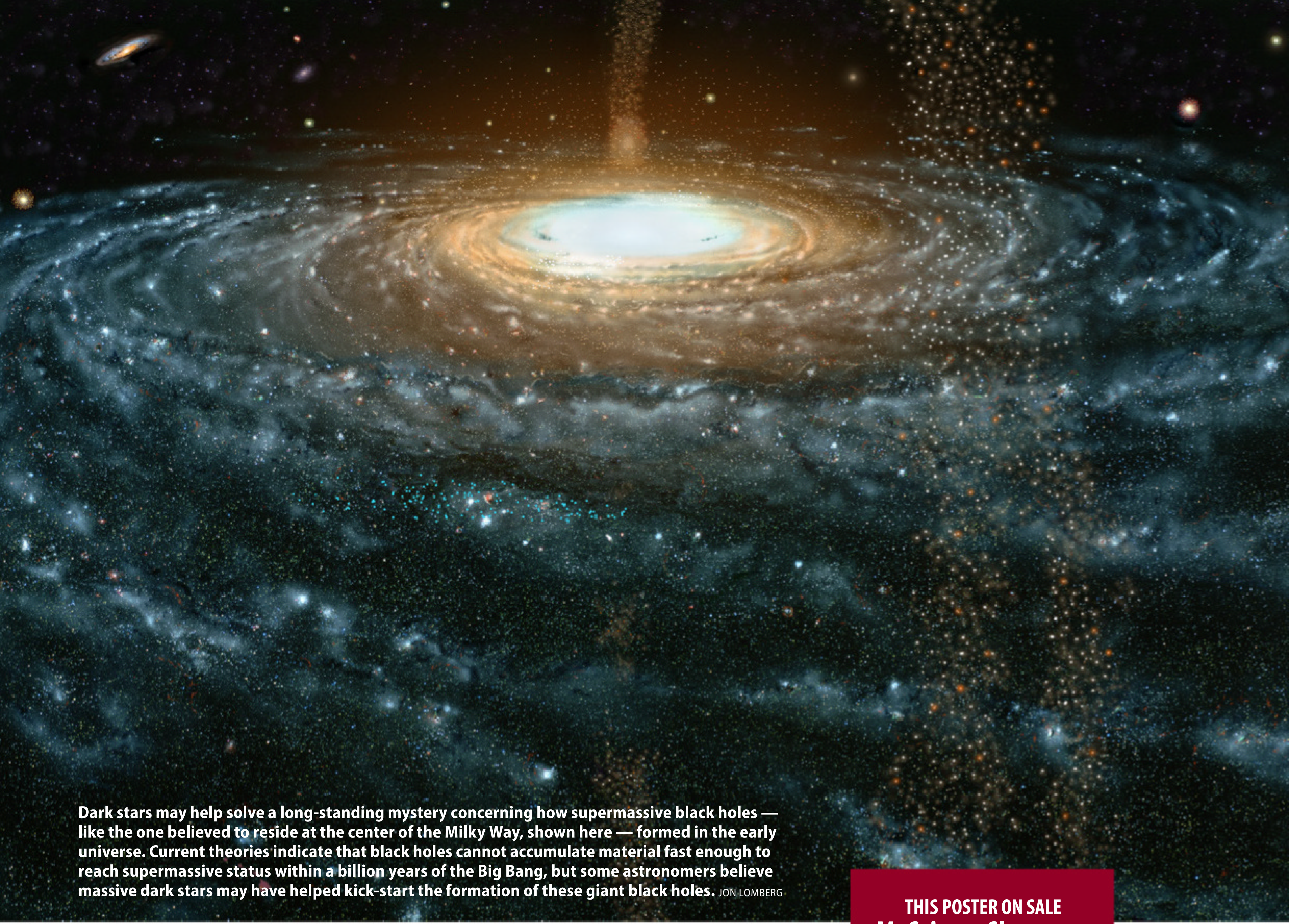
A leading theory on dark matter predicts the substance is in the form of weakly interacting massive particles — WIMPS for short. This class of particles is a natural consequence of the idea of supersymmetry, which is a part of the accepted standard model of particle physics, explaining how particles interact with each other and the fundamental forces of the universe.

Supersymmetry theory proposes that each type of particle has an identical, oppositely charged partner called an antiparticle. (Since WIMPS have no charge, they act as their own antiparticles.) When these partners — the particle and antiparticle — meet, they collide with a bang, utterly destroying one another in a shower of light, energy, and, in some cases, newly conceived lighter particles.


Collision of the WIMPS!
A shower of light & secondary particles

The universe's first stars didn't form overnight. It took around 200 million years after the Big Bang for star formation conditions to ripen — a process in which dark matter played a key role. Dark matter, ruled by gravity and unabated by interactions with light or baryonic matter, was the first material to start clustering in patches. Baryonic matter quickly followed and soon formed clumps a million times more massive than the Sun. These minihalos, as they are termed, became the nurseries for the first generation of stars, and they would eventually evolve into galaxies.

Back then, the universe was a denser and more compact place, and the WIMP partners tangoed with tenacity, continually annihilating each other in energetic blasts. During this time, WIMPs may have been swept up in the gravitational clutches of giant gas clouds. And as these clouds condensed to form early stars, they would have taken the WIMPs along for the ride.



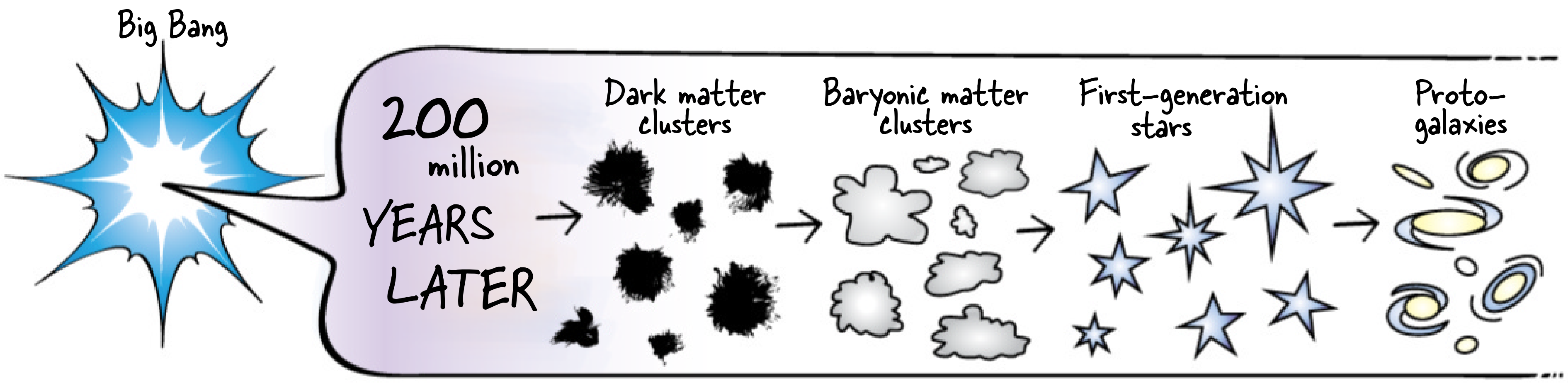
Dark stars may help solve a long-standing mystery concerning how supermassive black holes — like the one believed to reside at the center of the Milky Way, shown here — formed in the early universe. Current theories indicate that black holes cannot accumulate material fast enough to reach supermassive status within a billion years of the Big Bang, but some astronomers believe massive dark stars may have helped kick-start the formation of these giant black holes. JON LOMBERG

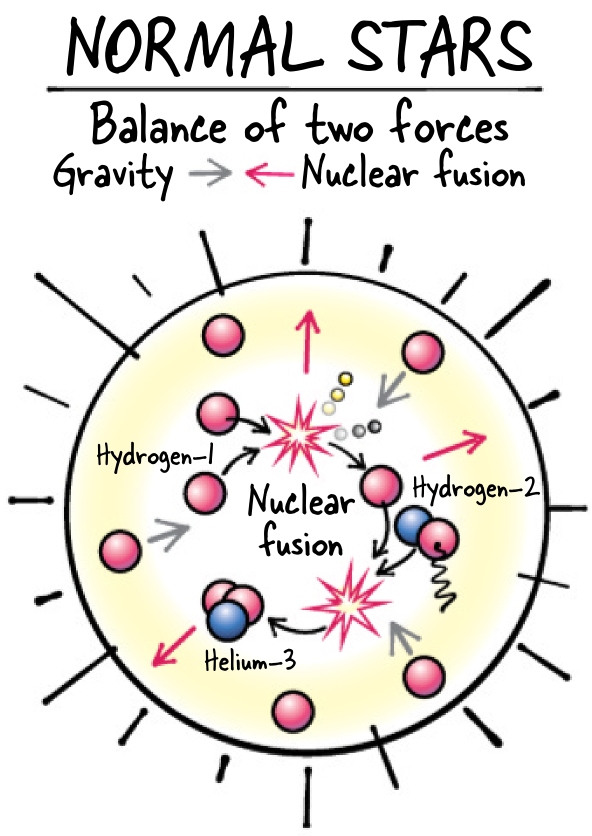
THIS POSTER ON SALE
MyScienceShop.com
Portrait of the Milky Way
by JON LOMBERG

Stars are normally supported by a delicate balance of forces: Gravity pulls the stellar atoms toward the center, while the forging of hydrogen into helium — the way a star powers and lights itself — creates an outward pressure. Annihilating dark matter throws a wrench into this system, with the energy from annihilation adding a powerful outward force. During star formation, the particles' annihilations would have at some point prevented the star from contracting further. At this time, the star would not have reached the density required to begin nuclear fusion, so the outward force generated by annihilating dark matter would solely balance the inward force of gravity.

Born in the dense early universe, these stars may have started out the size of our own Sun, but could have quickly grown a million times larger as they collected more material from their surroundings. But because they were heated in a different way, they were able to grow to much larger sizes than normal stars. (Dark stars would have been puffy giants. If one replaced the Sun, its extent would reach out past the orbit of Saturn.) Yet despite their immense size, it wouldn't have taken much dark matter to fuel them.

"[Dark stars] are almost entirely made of hydrogen. Only one part in a thousand is dark matter," says Katherine Freese, theoretical




NORMAL STARS
Balance of two forces
Gravity
Nuclear fusion
Hydrogen-1
Nuclear fusion
Hydrogen-2
Helium-3

The Bullet Cluster is a colliding pair of galaxy clusters some 3.7 billion light-years from Earth. Gravitational lensing studies of the Bullet Cluster have shown there is an offset between the overall mass and the baryonic mass of the galaxies, providing some of the strongest evidence yet for the existence of dark matter, which appears in blue in this image. NASA/ESA/STScI

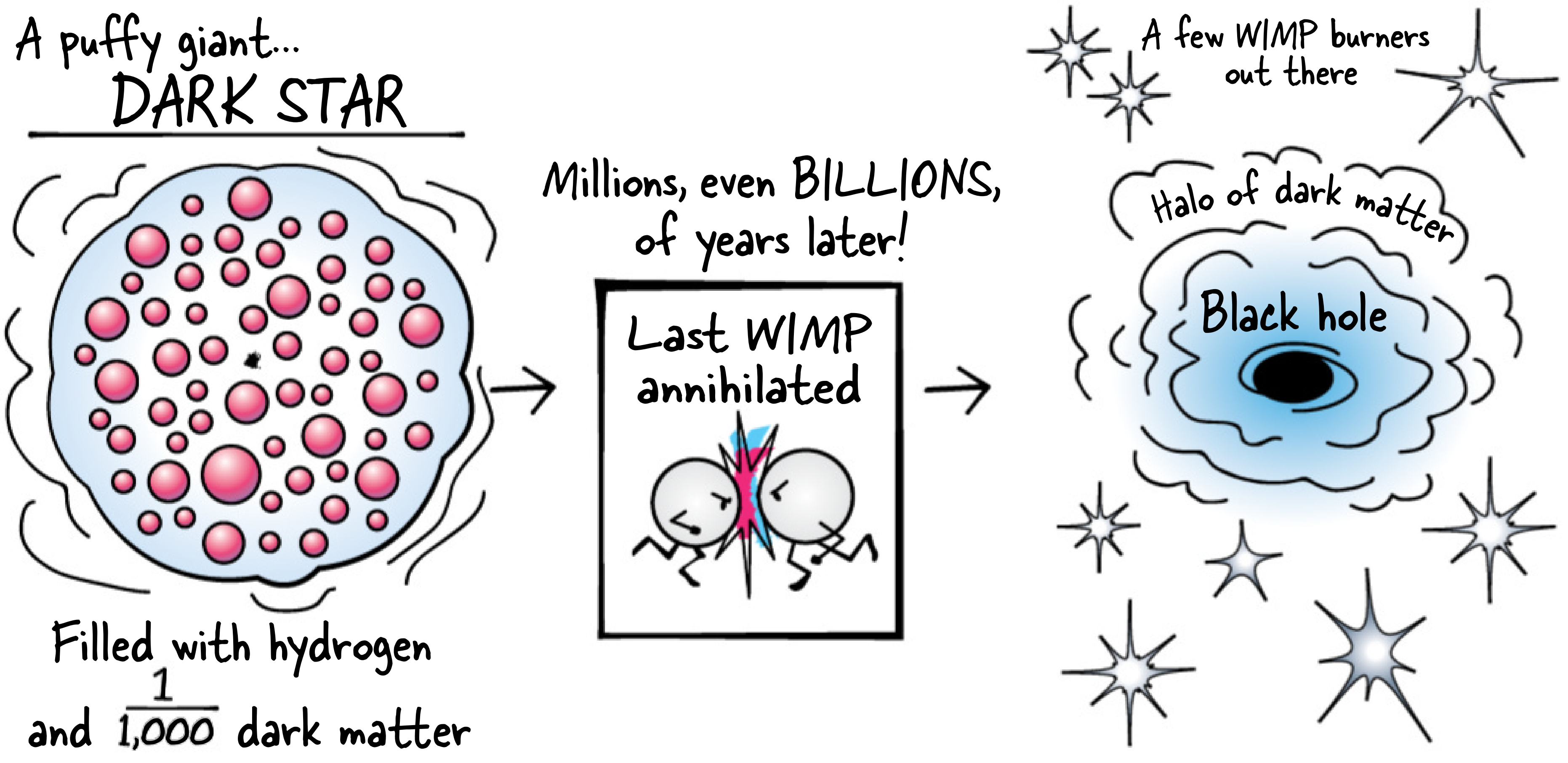
astrophysicist at the University of Michigan. Freese has pioneered the study of dark stars, which she conceived with colleagues about a decade ago.

Even at such a small amount, the dark matter fuel in a dark star is likely to power that star for millions or even billions of years. But as the last WIMPS annihilate, the star would have nothing remaining to counteract the force of gravity, and so it would begin to contract again. The smaller dark stars — a relative term meaning those only 100 times the mass of the Sun — would start nuclear fusion, giving them the power to sustain life as an active star a bit longer.

In today's expanded universe, the density of dark matter is much too low for it to power stars in the way it may have near the beginning.

"There is some dark matter going through the Earth and Sun," says Freese. "As the dark matter passes through, it collapses to the center where it annihilates. But it's not providing a heat source because there is not enough of it around."

Only at the centers of galaxies, where the dark matter density is highest, could dark stars potentially reside. Some scientists have predicted that there may be a few "WIMP burners" — white dwarf and neutron stars at the centers of galaxies — that have captured enough dark matter to at least partially fuel them. This extra power source likely would change the evolution and appearance of the star, acting like a stellar youth serum. Typically, these stars fade and cool at the ends of their lives, but the additional source of dark matter fuel would keep them abnormally hot,


A puffy giant...
DARK STAR
Filled with hydrogen
and 1/1,000 dark matter
Millions, even BILLIONS, of years later!
Last WIMP annihilated
A few WIMP burners out there
Halo of dark matter
Black hole

making them look much younger than they actually are. Theoretically, these stars should be observable, though none have been found to date.

Cosmic clues

Eventually all dark stars collapse into black holes. Indeed, these unique stellar objects might help solve a long-standing mystery of the early universe: the origin of supermassive black holes. Observations have found numerous giant black holes — a million to a billion times the mass of the Sun — in the early universe, but theorists are uncertain how such massive black holes could have formed in so little time.

Standing theories for black hole formation have limitations on the speed at which a black hole can accumulate mass. These speeds are far below that necessary for a supermassive black hole to form within the first billion years of the universe, where many have been found. Dark stars, which can grow much larger than typical stars and thus create much larger black holes, could represent one seed from which supermassive black holes may have grown in the early universe. "Currently there really is no good answer, and this could provide a solution," says Freese of supermassive black hole formation.

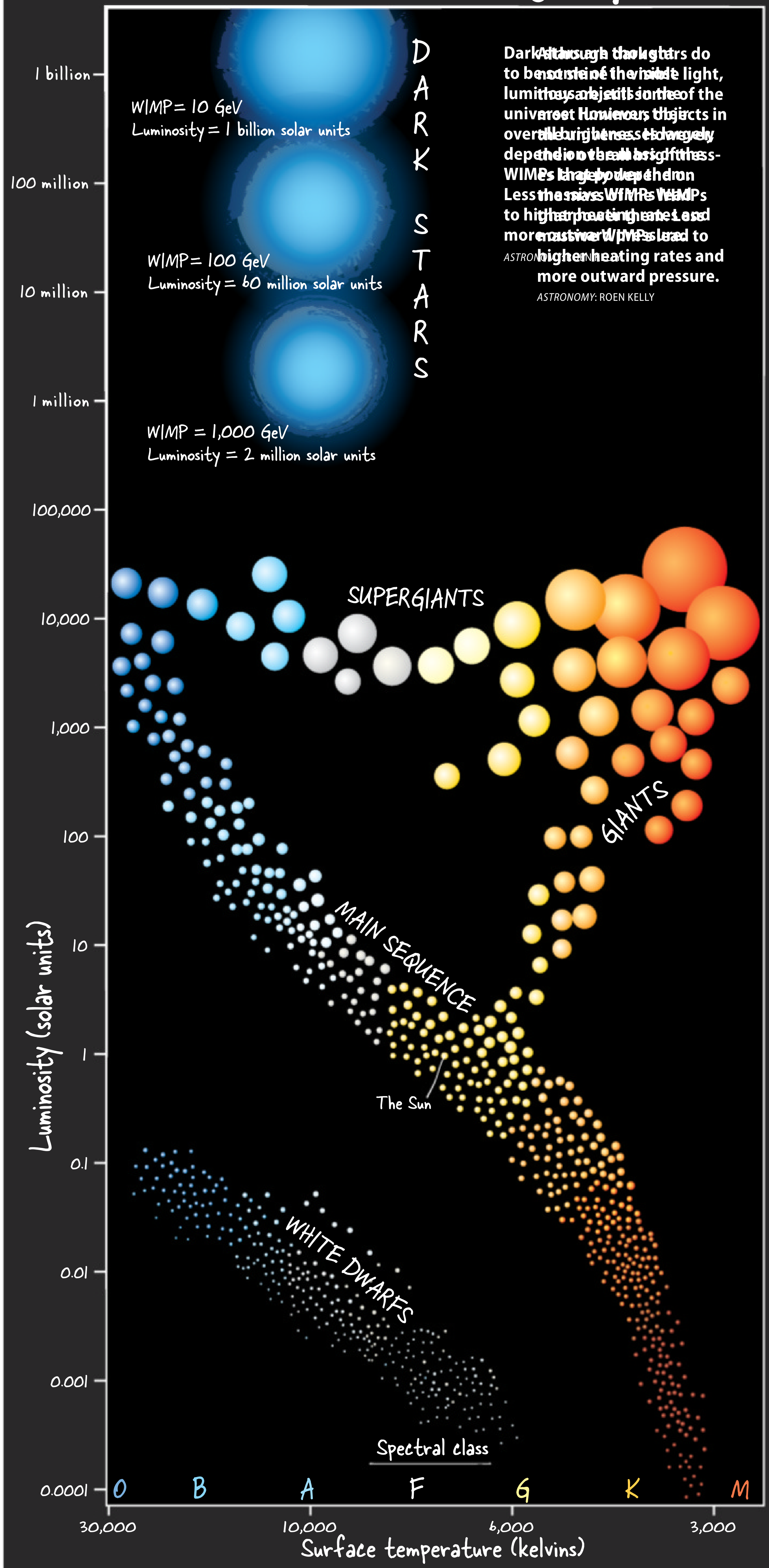
Dark stars, if discovered, could also help scientists better understand dark matter. "The physics of the dark stars, and the way we observe them, potentially will then tell us about the dark matter particle that underlies it," says Tanja Rindler-Daller, an astrophysicist at the University of Vienna. "Some of these stellar properties depend on the mass of the dark matter particle."

Rindler-Daller studies dark stars with computer models, specifically looking at ways the stars might pulsate. Many stars periodically expand and contract, causing their light to pulse, and dark stars might show this behavior as well. Comparing different models, Rindler-Daller discovered that different masses of WIMPs would lead to different periods of variability in the dark stars. If observed, these pulsations could be one way to measure the mass of WIMPs.

The pulsations could also eventually be used as a measuring stick in the early universe. Cepheid variable stars, whose pulsations and physics are known in

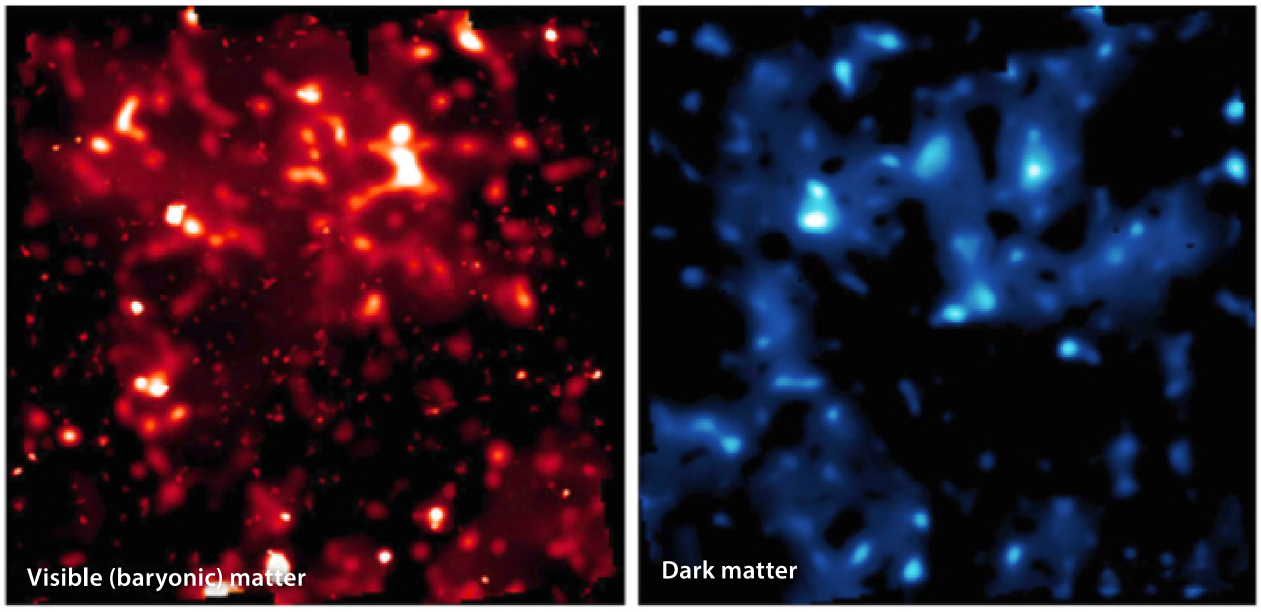
Dark stars burn brightly

Dark stars burn brightly



Although dark stars do not shine in the visible light, they are still some of the most luminous objects in the universe. However, their overall brightness is largely dependent on the mass of the WIMPs that power them. Less massive WIMPs lead to higher heating rates and more outward pressure.

ASTRONOMY: ROEN KELLY

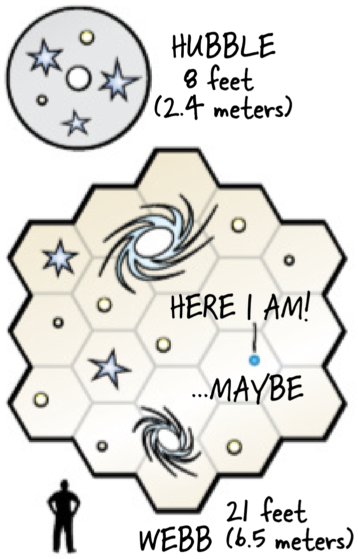


These false-color images captured by the Hubble Space Telescope compare the distribution of normal matter (red) to dark matter (blue) in the universe. The map covers an area of the sky nine times larger than the Full Moon, making it one of the best maps of dark matter ever obtained. NASA/ESA/R. MASSEY

great detail, have been used extensively to measure the distances between galaxies. However, Cepheids are not bright enough to be seen in the early universe — at what astronomers refer to as high redshift.

"Dark stars are harder to use because we would need to study them in detail once we found them," says Rindler-Daller. "Only once we understood them, we could then also use this as an indicator to measure the distance to galaxies at high redshift."

While it's theoretically possible to use dark stars to measure the universe, it would require finding many of these objects. And for now, scientists are simply hoping to find one.



Seeing in the dark

No current telescope is powerful enough to see a dark star in the early universe. But this will soon change. The James Webb Space Telescope, the successor to the Hubble Space Telescope, is set to launch in 2021. With a 6.5-meter primary mirror and special instruments built for capturing infrared light, the James Webb should be able to see protogalaxies and dark stars, should they exist, in the early universe.

"There's not a whole lot around in the early universe, so there's not much competing stuff. The standard first stars without dark matter are too small and too faint to be seen by James Webb," says Freese. If something extremely luminous is found in the early universe, dark stars will be a leading candidate. However, dark stars will still need to be big enough and bright enough in order to be seen.

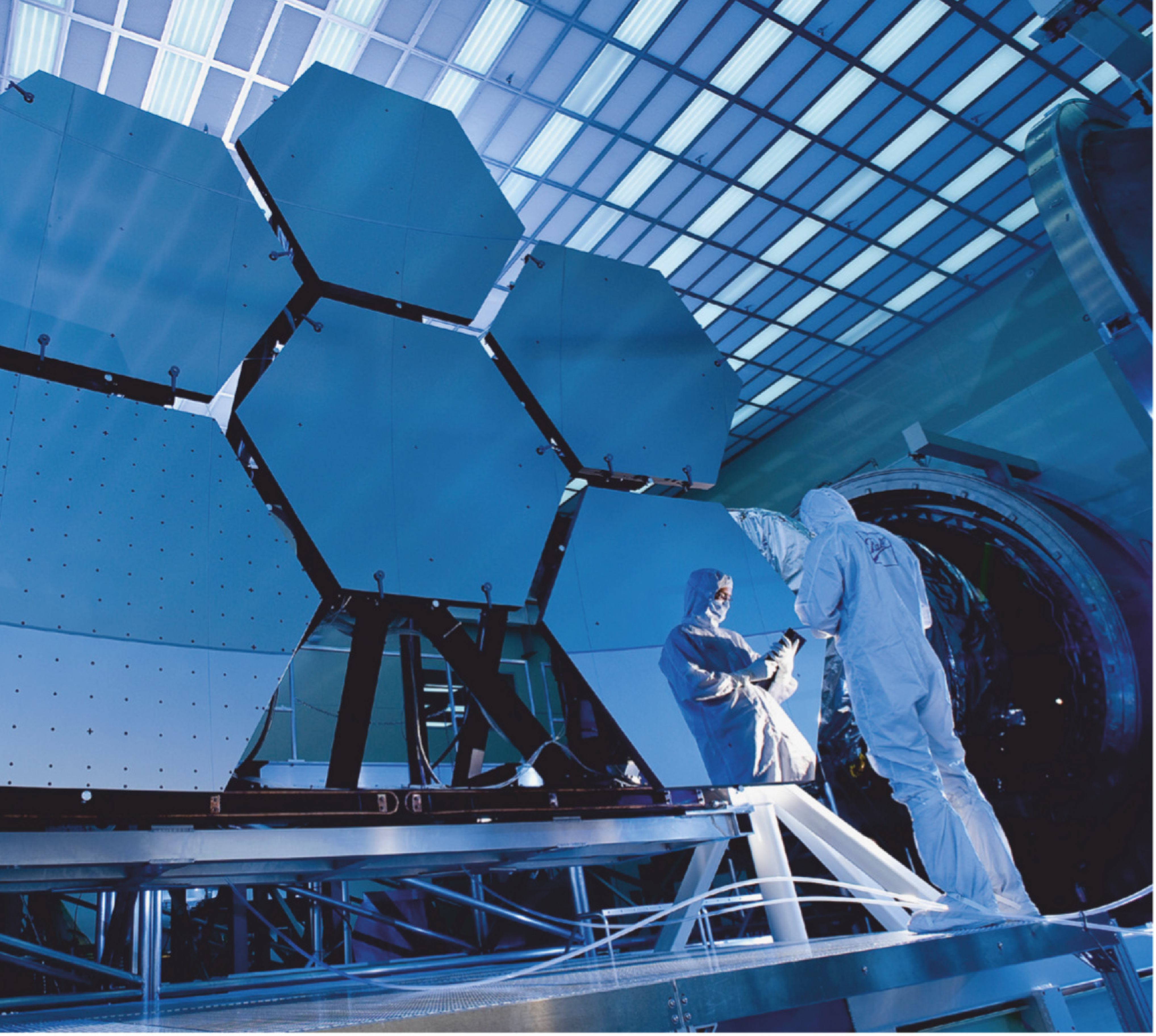
"If dark matter is made of WIMPS, I really believe dark stars exist. Now if they start out at one solar mass and start accreting, the question is how big can they get before the accretion stops?" says Freese. "If they stop at a thousand solar masses, then James Webb can't see them. So they might exist, but in my lifetime I'll never see them."

Dark stars could further be distinguished from other cosmic bodies in the early universe by the type of light they give off. Dark stars are relatively cool — only around 10,000 kelvins (17,500 degrees Fahrenheit, 9,700 degrees Celsius) — and would radiate at longer wavelengths than warmer objects.

Pulsations such as those Rindler-Daller suspects would also be a dead giveaway, as no star is known to vary in that manner. Though dark stars should pulsate over periods of weeks, by the time the star's light reaches us, the expansion of the universe will have stretched out the light so much that the pulsations we observe will last over a period of a hundred days or more. Observing a dark star over such a lengthy period would be financially and logistically challenging, but it would provide the best proof for the stars' existence.

Even if the James Webb Space Telescope detects no dark stars, there might be other ways to find them. Gravitational wave detectors like LIGO have been pushing the boundaries of astronomy, finding signatures of colliding black holes and neutron stars. A collision between two dark stars could create gravitational waves that are detectable by these instruments, and would also yield signatures that may distinguish them from merging black holes.

Additionally, the next generation of ground-based telescopes, with mirrors 30 meters across, is at the drawing board. Infrared detectors on these telescopes could easily peer into the dusty interior of our galaxy. Astronomers may



When the James Webb Space Telescope launches in 2021, its unprecedented resolution will allow astronomers to observe some of the most distant objects in the universe, including dark stars — if they exist. In this image, six of Webb's 18 mirrors are being subjected to temperatures as low as 24 kelvins (–416 F, –249 C) to measure how the shape of each mirror changes. NASA/MSFC/DAVID HIGGINBOTHAM/EMMETT GIVEN

be able to find, hidden near the center of the Milky Way, old white dwarfs and neutron star WIMP burners whose lives have been extended, thanks to dark matter accretion.

It also may be possible to see the byproducts of WIMP annihilations. The black holes created by dark stars will likely have halos of dark matter that never made it into the star. The annihilation of this dark matter could produce enough gamma rays to be seen by NASA's Fermi Gamma-ray Telescope, which has been scoping out high-energy light from across the cosmos since its launch in 2008.

A shadowy future

While dark stars remain in the theoretical realm for now, their existence is inferred based on real science, and it may not be long until the first are found.

"The dark matter particle which underlies this dark star idea is really a very prominent one. It's the WIMP dark matter, which is still the most prominent and plausible candidate for dark matter," says Rindler-Daller. "These dark stars don't require some exotic dark matter no one has heard of — it's really the standard dark matter particles which would be able to have this effect on the first stars."

Though only a handful of scientists are currently dedicated to studying these objects, Freese expects the field to grow in the future. "We've made a prediction, so if you see something that looks like that, then the motivation for studying dark stars will go through the roof," she says.

In the meantime, scientists will continue searching for these peculiar objects, hoping to reveal more clues about how and where they might someday be found.

Mara Johnson-Groh *is a science writer and photographer who writes about everything under the Sun, and even things beyond it.*

WHY DO GALAXIES ALIGN?

The matter in our universe forms filaments and threads like a grand cosmic web, tugging galaxies and clusters into place along the way.

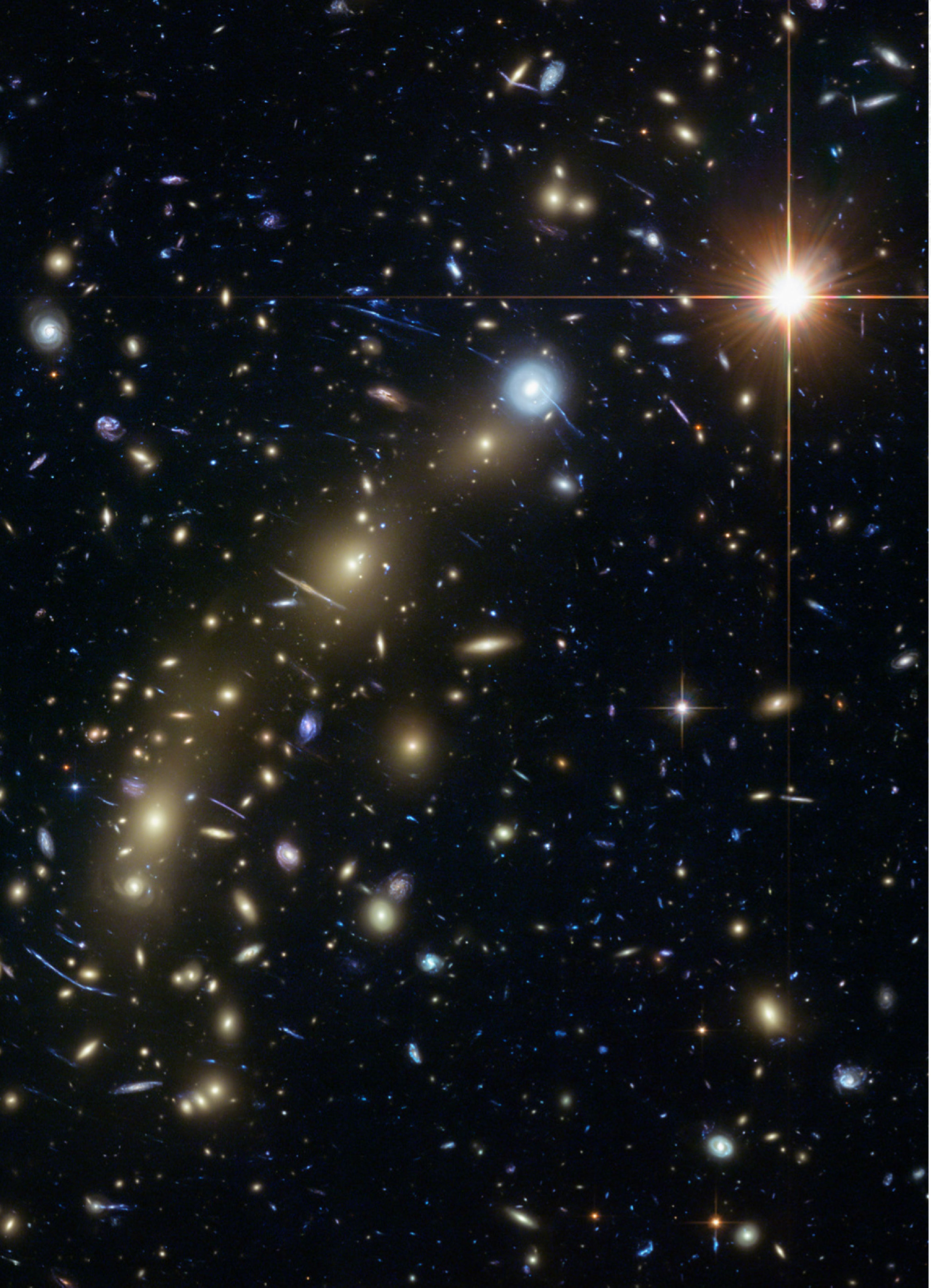
by Michael West

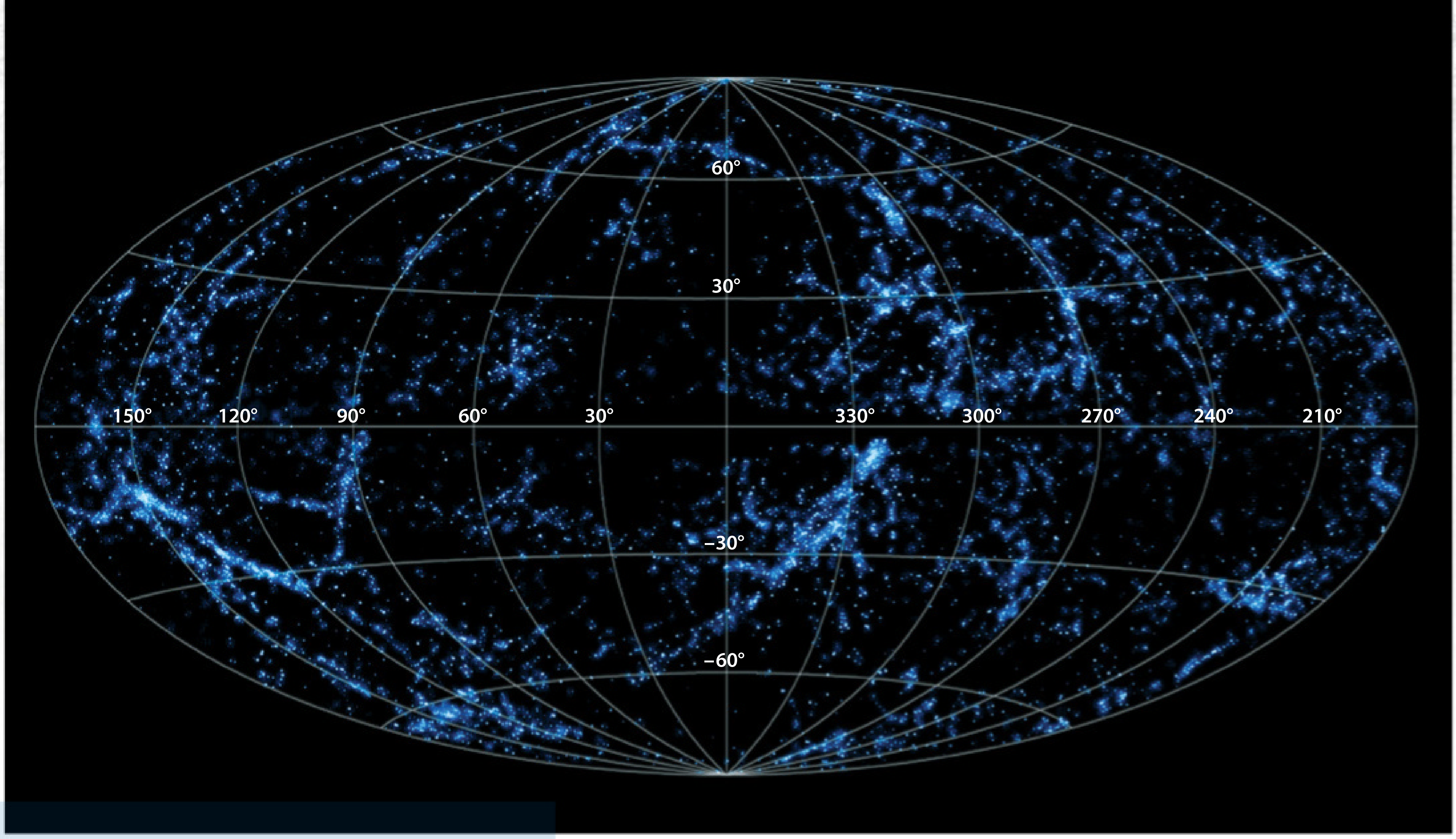
The galaxy cluster MACS J0416.1–2403 is highly elongated. The orientations of its brightest member galaxies, which appear round and yellow in this image, reflect this arrangement. ESA/HUBBLE, NASA, AND HST FRONTIER FIELDS

One of the most striking features of the distribution of matter in the universe is its filamentary appearance, with long, luminous strands of galaxies woven together into a vast cosmic web.

Nowhere is this more evident than the Perseus-Pisces Supercluster. This colossal chain of galaxies snakes across more than 50° of the northern sky, fed by a network of smaller filaments that resemble tributaries flowing into a river. Embedded within these filaments are densely populated groups and clusters of galaxies. Between them lie immense voids.

Our own Milky Way Galaxy resides in the outskirts of a similar structure known as the Laniakea Supercluster. (*Laniakea* means “immeasurable heaven” in Hawaiian.) Home to an estimated 100,000 galaxies, it’s a tangled knot of





A slice from the all-sky 2MASS XSCz infrared survey shows galaxies within 140 million to 280 million light-years of Earth. Long chains of galaxies — filaments — are seen stretching across vast expanses of space, linking together to create an intricate network known as the cosmic web. TOM JARRETT (IPAC/CALTECH)

filaments stretching half a billion light-years from end to end. University of Hawai'i astronomer Brent Tully, whose team discovered Laniakea in 2014, likened it to "finding out for the first time that your hometown is actually part of a much larger country that borders other nations."

Everywhere we look, galaxies trace out the paths of these filaments. But it turns out galaxies don't just illuminate the cosmic web — they're also shaped by it.

When the stars align

In 1874, less than a decade after the Civil War ended and long before anybody knew for certain what galaxies were, astronomer Cleveland Abbe wondered how "nebulae," as galaxies were known in those days, are oriented in space.

To answer this question, Abbe chose 59 of the most extended nebulae in Sir John Herschel's famous *Catalogue of Nebulae and Clusters of Stars* and measured their direction of elongation. His surprising conclusion was that the nebulae appeared to favor certain orientations with respect to the Milky Way. But his study drew little attention and was soon forgotten; Abbe moved on to a more successful career in meteorology.

Forty years later, American astronomer Edward Fath revisited Abbe's question. After measuring the orientations of hundreds of galaxies on photographic plates taken at Mount Wilson Observatory, he reported in 1914 that they "appear to be oriented at random."

Decades of lively debate followed. English amateur astronomer Francis Brown spent more than 30 years investigating galaxy alignments in his spare time. In a series of papers published between 1938 and 1968, he presented evidence that galaxy orientations in certain regions of the sky were far from random. But many astronomers remained skeptical, suggesting that the results might be a consequence of measurement errors, selection effects, or even psychological biases.

Then in 1968, Gummuluru Sastry of Wesleyan University showed beyond any doubt that the orientations of some galaxies are clearly not haphazard. Sastry discovered that giant elliptical galaxies that populate the centers of clusters — the biggest and brightest galaxies in the universe — have a remarkable tendency to be elongated in the same direction as their host cluster. For example, if a cluster is elongated north-south, then more often than not, its brightest member galaxy is, too. If galaxies were human, psychologists would call this a textbook example of mirroring behavior.

Although Sastry's conclusion was based on only five galaxies, other astronomers have subsequently confirmed his results with much larger samples. Recent studies with the Hubble Space Telescope — whose sharp vision allows us to see the remote past by looking far into space — reveal that these alignments even existed billions of years ago.

And there's more.

In 1981, Bruno Binggeli of the University of Basel in Switzerland showed that clusters of galaxies aren't oriented at random, either. Instead, they exhibit a remarkable tendency to "point" toward neighboring clusters. Binggeli's discovery was anticipated a few years earlier by Estonian astronomers Jaan Einasto, Mihkel Jõeveer, and Enn Saar.

WHY ARE GALAXIES ELONGATED?

Most galaxies are elongated in shape; round ones are rare. But why?

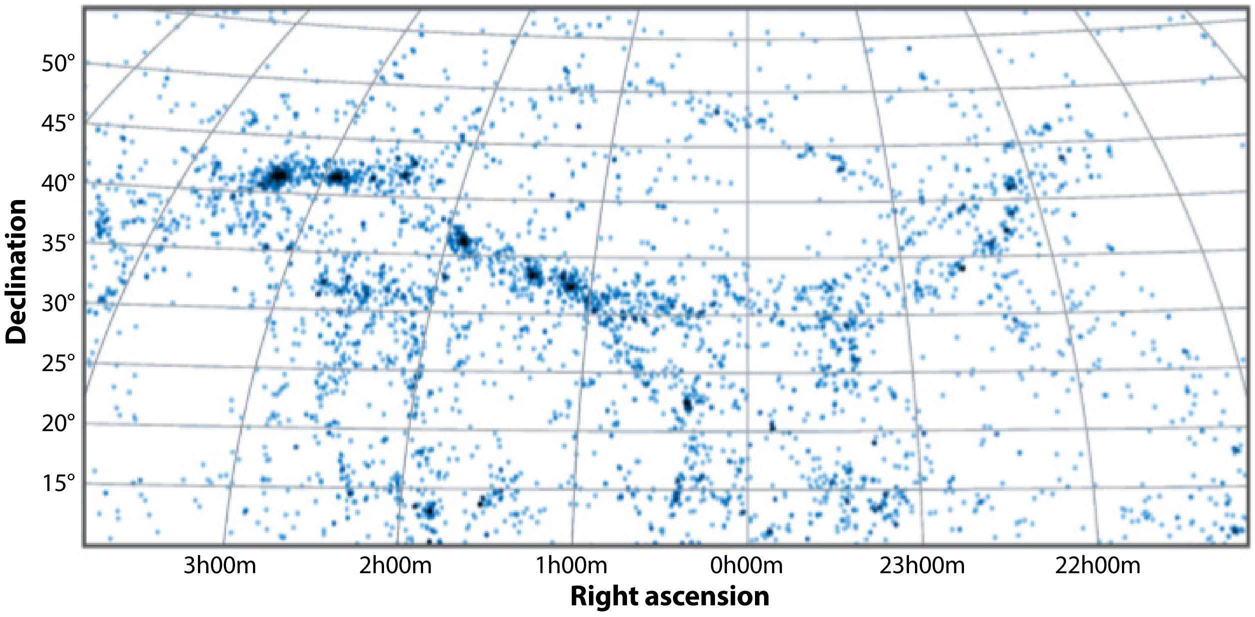
A galaxy's image is a snapshot of its stars' motions, a moment frozen in time. Spiral galaxies like the Milky Way owe their flattened shapes to rotation. Just as a ball of pizza dough flattens when spun, a spiral galaxy's stars spread into a thin disk as it rotates. Traveling at half a million miles per hour, our Sun has made nearly two dozen trips around the Milky Way since its birth.

Elliptical galaxies, on the other hand, have little or no rotation. Their stars swarm around the galaxy's center like bees around a hive, each following its own seemingly random path. However, these orbits are often elongated in one direction more than others, stretching the galaxy into a shape resembling a luminescent football. —*M.W.*

FROM TOP: The giant galaxy in the center of the cluster Abell 3827 is in the process of devouring several smaller ones. Galaxies like this grow by first capturing and then cannibalizing their neighbors. R. CARRASCO ET AL., GEMINI OBSERVATORY/AURA

Galaxy mergers often occur along filaments in the cosmic web, possibly imparting the end result with a preferred alignment. ESA/HUBBLE AND NASA; ACKNOWLEDGEMENT: JUDY SCHMIDT (GECKZILLA)

Cosmic cartography



On this map of the galaxy distribution in the region of the Perseus-Pisces Supercluster, each point represents a galaxy located 150 million to 300 million light-years from Earth. Dense clusters of galaxies, the metropolises of the cosmos, dot the prominent filament like beads on a string. MICHAEL WEST

SMEARING COSMIC SHEAR

One astronomer's signal is sometimes another's noise.

Charles Messier compiled his famous list of deep-sky objects to spare fellow comet hunters from wasting time on them. Edmund Weiss, a 19th-century Austrian astronomer, called asteroids the "vermin of the sky" because their trails on long-exposure photographs were considered blemishes. And galaxy alignments turn out to be a nuisance for some astronomers, too.

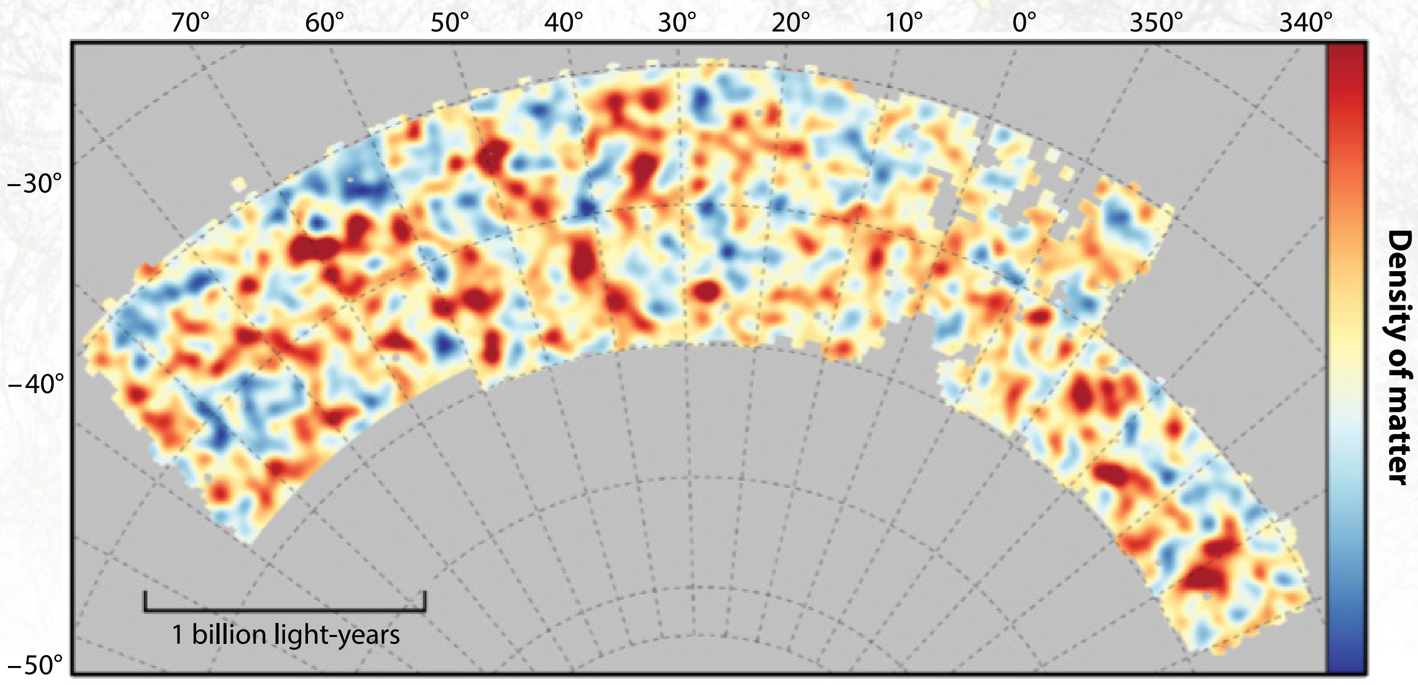
Gravitational lensing, the deflection of light rays by gravity, has become a powerful tool for cosmology. As light from faraway galaxies journeys through space, the gravitational pull of matter — both visible and invisible — alters its path. This causes galaxies near each other in the sky to appear slightly elongated and aligned. Astronomers call these distortions cosmic shear.

Although it's a minuscule effect, by carefully measuring the shapes and orientations of large numbers of galaxies, astronomers can infer the amount and distribution of dark matter, the mysterious stuff that makes up much of the universe.

But a crucial assumption in cosmic shear studies is that galaxy orientations are inherently random, so that any apparent alignments are the result of gravitational lensing. Physical alignments, such as those seen in giant elliptical galaxies, masquerade as cosmic shear and complicate analysis.

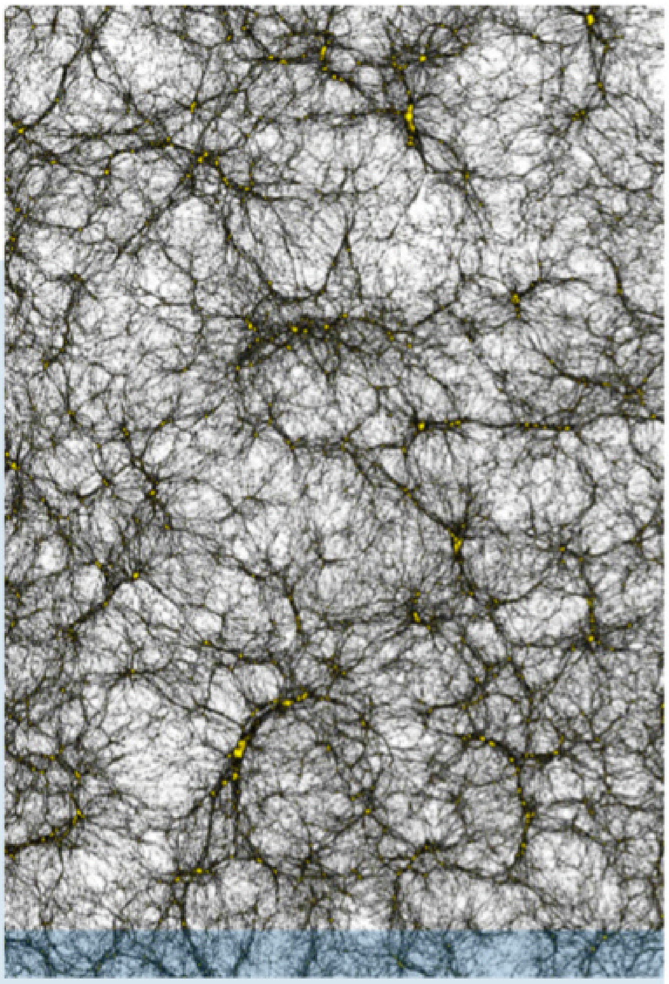
So, while intrinsic alignments provide important clues about how environment shapes galaxies, they're a nuisance for scientists whose goal is mapping the dark matter content of the universe. —*M.W.*

Dark matter distribution



An international team of scientists used the 570-megapixel Dark Energy Camera at Cerro Tololo Inter-American Observatory in Chile to record light from 26 million galaxies. Tiny distortions in their apparent shapes caused by gravitational lensing provide a map of the dark matter in different regions of space. In this image, red regions have more dark matter than average, while blue regions have less. Hints of large-scale filamentary features can be seen. In the future, the European Space Agency's Euclid mission and NASA's Wide Field Infrared Survey Telescope will measure cosmic shear from space, providing even sharper views of the cosmic dark matter distribution.

CHIHWAY CHANG OF THE KAVLI INSTITUTE FOR COSMOLOGICAL PHYSICS AT THE UNIVERSITY OF CHICAGO AND THE DES COLLABORATION



A computer simulation shows the gossamer-like structure of the cosmic web. Within this network, matter flows along filaments, piling up where they intersect. The simulation shown here, one of the largest ever done, followed the motion of trillions of particles as gravity amplified tiny variations in their initial distribution. Black points show the locations of dark matter; yellow denotes dense regions where galaxies and clusters form; and white indicates voids. The region displayed here is 2.5 billion light-years across, only a portion of the entire simulated volume. JOACHIM STADEL, UZH

They noticed that clusters in the Perseus-Pisces Supercluster are elongated in the same direction as the filament that bridges them, leading them to suggest in a 1980 paper published in *Monthly Notices of the Royal Astronomical Society* that "the orientation of clusters in superclusters is a conspicuous morphological property of superclusters."

The alignment of galaxies and clusters over tens or hundreds of millions of light-years means the innermost regions of some galaxies are aligned with their surroundings on scales larger than 1,000 times the size of a single galaxy itself. It suggests that the birth and evolution of these objects have been strongly influenced by the cosmic web. But how?

Going with the flow

Galaxies, like people, are products of their environment. Elliptical galaxies, for example, usually huddle together in groups and clusters, while spiral galaxies prefer more elbowroom.

Environment clearly plays a role in galaxy orientations, too. There are two leading theories for how this happens. One suggests that galaxies are born aligned with their surroundings, while the other assumes that alignment is something they acquire later.

Galaxies might gain their orientation in several ways. Big galaxies grow by cannibalizing smaller ones, a process astronomers euphemistically call merging. But mergers aren't haphazard. Computer simulations show that they occur most frequently along well-defined

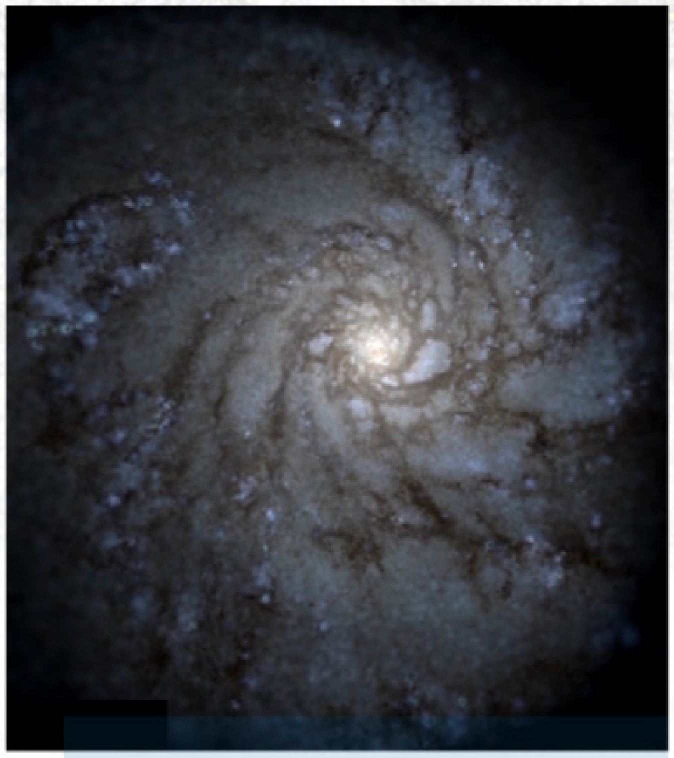
SIMULATING THE UNIVERSE

In 1941, five years before digital computers were invented, Erik Holmberg of Lund Observatory in Sweden performed the first simulation of colliding galaxies. What he lacked in computational power he made up for with ingenuity.

Because an object's gravitational pull and apparent brightness both vary inversely with the square of distance, Holmberg realized he could use light as a proxy for gravity. Representing two galaxies with 37 lightbulbs each, he measured the brightness at different locations to determine the strength and direction of the gravitational force and adjusted their motions accordingly. Although crude, Holmberg's analog computation provided insights into the frequency of galaxy mergers and suggested that close encounters could generate spiral arms.

Astronomers quickly embraced digital computers as a tool to simulate events and timescales beyond anything accessible to mere mortals. In the 1970s, brothers Alar and Juri Toomre pioneered numerical simulations of galaxy mergers by representing each galaxy as a swarm of interacting particles whose trajectories were calculated by the computer. Although the available computing power at the time limited the number of particles that could be followed, these simulations revealed that galaxy mergers are common, and that mergers of spiral galaxies can produce things that look like elliptical galaxies.

As computational power grew, so did astronomers' ambition. Today, thanks to state-of-the-art computers, it's possible to simulate the evolution of enormous volumes of space in unprecedented detail using trillions of particles to represent both luminous and dark matter. Beginning from some assumed set of initial conditions, astronomers can run the simulation forward in time to see what the predicted distribution and properties of galaxies would be today and then compare the results with observations. Such simulations have become an invaluable tool for understanding how the universe reached its present state. —*M.W.*



A computer simulation of our home galaxy, the Milky Way. Today's simulations are more realistic than ever before, following the birth and evolution of galaxies from the Big Bang to the present day. This simulation required 15 days of number crunching with one of the world's fastest supercomputers. HOPKINS RESEARCH GROUP/CALTECH

MRC 1138-262, the Spiderweb Galaxy, is seen in this Hubble Space Telescope image as it appeared only 2 billion years after the Big Bang. The giant galaxy, located at the center of a growing cluster, is being assembled via mergers of smaller systems of gas, dust, and stars. Such mergers occur preferentially along directions defined by the surrounding cosmic web. NASA, ESA, G. MILEY, R. OVERZIER AND THE ACS SCIENCE TEAM

directions as gravity shepherds material along filaments. This imprints a built-in memory of their environment on these cannibals, one that reflects the surrounding cosmic web. In a sense, giant galaxies are like spiders waiting for prey, only it is smaller galaxies rather than bugs that they devour, and the web they sit in is elongated rather than circular.

Alternatively, given enough time, gravity's relentless tug will slowly reorient galaxies until they align with their surroundings. Theoretical calculations and computer simulations suggest this should occur on timescales shorter than the age of the universe, which means that even if a galaxy was initially misaligned with its surroundings, it should have fallen into line by today.

As is often the case in science, it's possible, even likely, that there's more than one explanation for galaxy alignments, with mergers along filaments and twisting due to gravitational effects both contributing to the end result.

Is there more to cosmic congruence?

"Things are the way they are because they were the way they were," maverick astronomer Fred Hoyle once quipped.

Beginning with the thinnest of strands — tiny irregularities in the primordial distribution of matter — gravity has slowly woven a cosmic web of sublime beauty and complexity. It's astonishing to think that the filamentary distribution of matter on large scales is not only traced by galaxies and clusters, but also reflected in their orientations.

There's tantalizing evidence that alignments might even extend to other scales. In 2014, a team led by Damien Hutsemékers from the University of Liège in Belgium reported that the spin axes of some quasars are parallel to each other over distances of billions of light-years, and that they share the same orientation as the surrounding filamentary structure.

If confirmed, this would suggest that the cosmic web has even influenced the supermassive black holes powering quasars, further evidence of a truly remarkable coherence of structures in the universe.

GARGANTUAN GALAXIES

People come in a wide range of shapes and sizes. According to *Guinness World Records*, the heaviest person ever was an American named Jon Brower Minnoch, who tipped the scales at a whopping 1,400 pounds (635 kilograms). At the other extreme, a Mexican woman named Lucia Zarate, who suffered from an extreme form of dwarfism, weighed only 13 pounds (6 kg) as an adult — less than 1 percent of Minnoch's weight.

But that's nothing compared to galaxies, where the biggest outweigh the smallest by factors of a million or more. Lurking in the centers of many galaxy clusters are the largest known stellar systems in the universe, giant elliptical galaxies that could easily swallow dozens of their neighbors — and probably have. It may be no coincidence that these behemoths are so strongly aligned with their surroundings. *—M.W.*

Michael West *is deputy director for science at Lowell Observatory in Flagstaff, Arizona. His most recent book is* A Sky Wonderful With Stars: 50 Years of Modern Astronomy on Maunakea.

Do all galaxies have dark

The discovery of two ghostly galaxies created a hullabaloo in the astronomical community. But the jury's still out on what's really going on. **by Jake Parks**

matter?

Some 60 million light-years from Earth — by some researchers' estimate, anyway — a pair of strange galaxies is causing a cosmic stir. These island universes hold far fewer stars than your average galaxy. But it's not the lack of stars that surprises astronomers. The bizarre galaxies, named NGC 1052-DF2 and NGC 1052-DF4 (or DF2 and DF4, for short), also seem to lack any significant amount of dark matter.

Because the duo could be the first known galaxies without the substance, which accounts for 85 percent of the universe's matter, news of DF2's discovery in 2018 quickly spread throughout the astronomical community. If confirmed, such galaxies without dark matter would throw a wrench into our understanding of how galaxies form and evolve.

"We thought that every galaxy had dark matter and that dark matter is how a galaxy begins," astrophysicist Pieter van Dokkum of Yale University, lead author of the initial paper on DF2, said in a press release. "This invisible, mysterious substance is the most dominant aspect of any galaxy. So finding a galaxy without it is unexpected. It challenges the standard ideas of how we think galaxies work, and it shows that dark matter is real: It has its own separate existence apart from other components of galaxies."

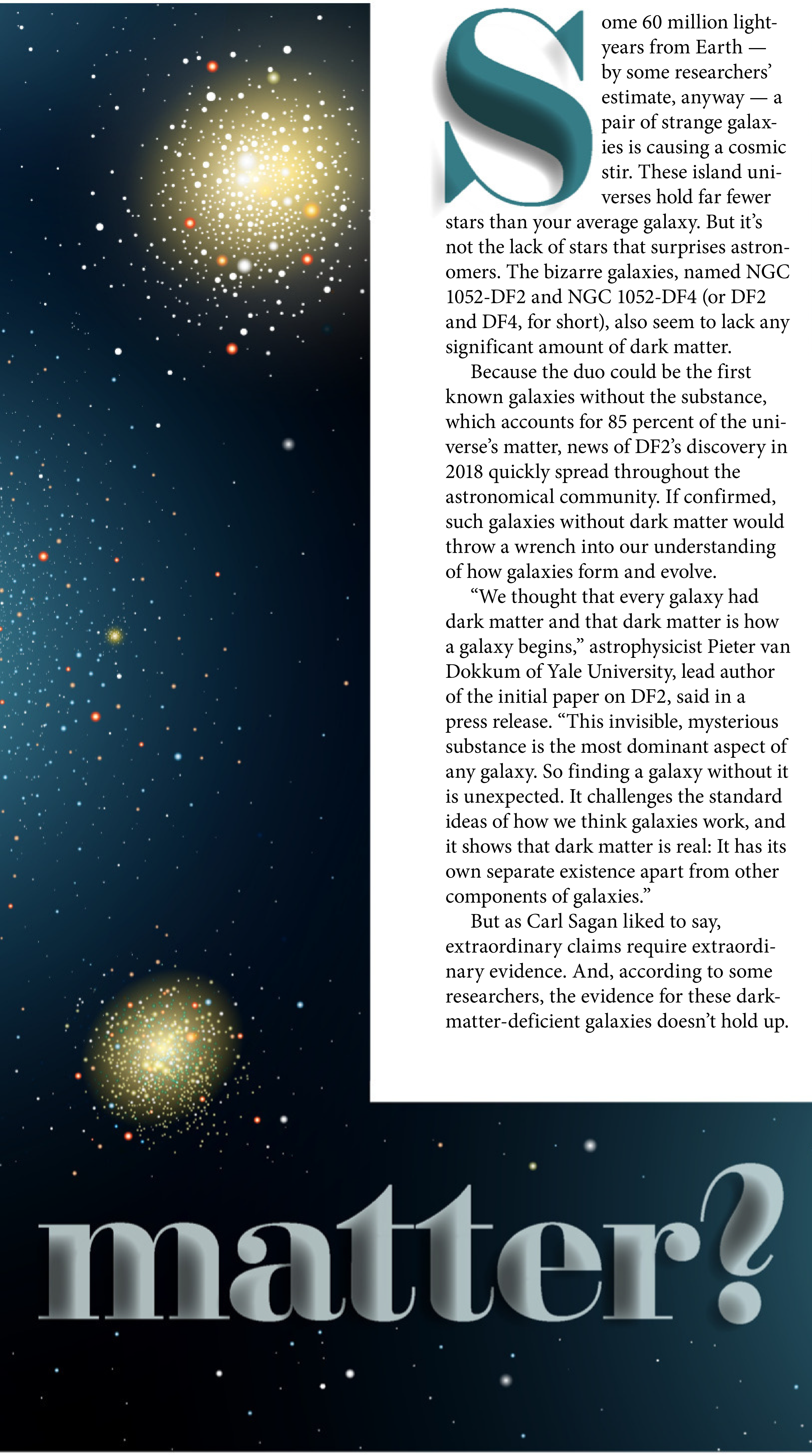
But as Carl Sagan liked to say, extraordinary claims require extraordinary evidence. And, according to some researchers, the evidence for these dark-matter-deficient galaxies doesn't hold up.

Stationed in New Mexico, the novel Dragonfly Telephoto Array has been built up over the years into a collection of 48 telephoto lenses bundled in two groups. Together, the 400mm lenses create the equivalent of a 1-meter refracting telescope and enable observations of extremely faint and diffuse cosmic structures. P. VAN DOKKUM (YALE)

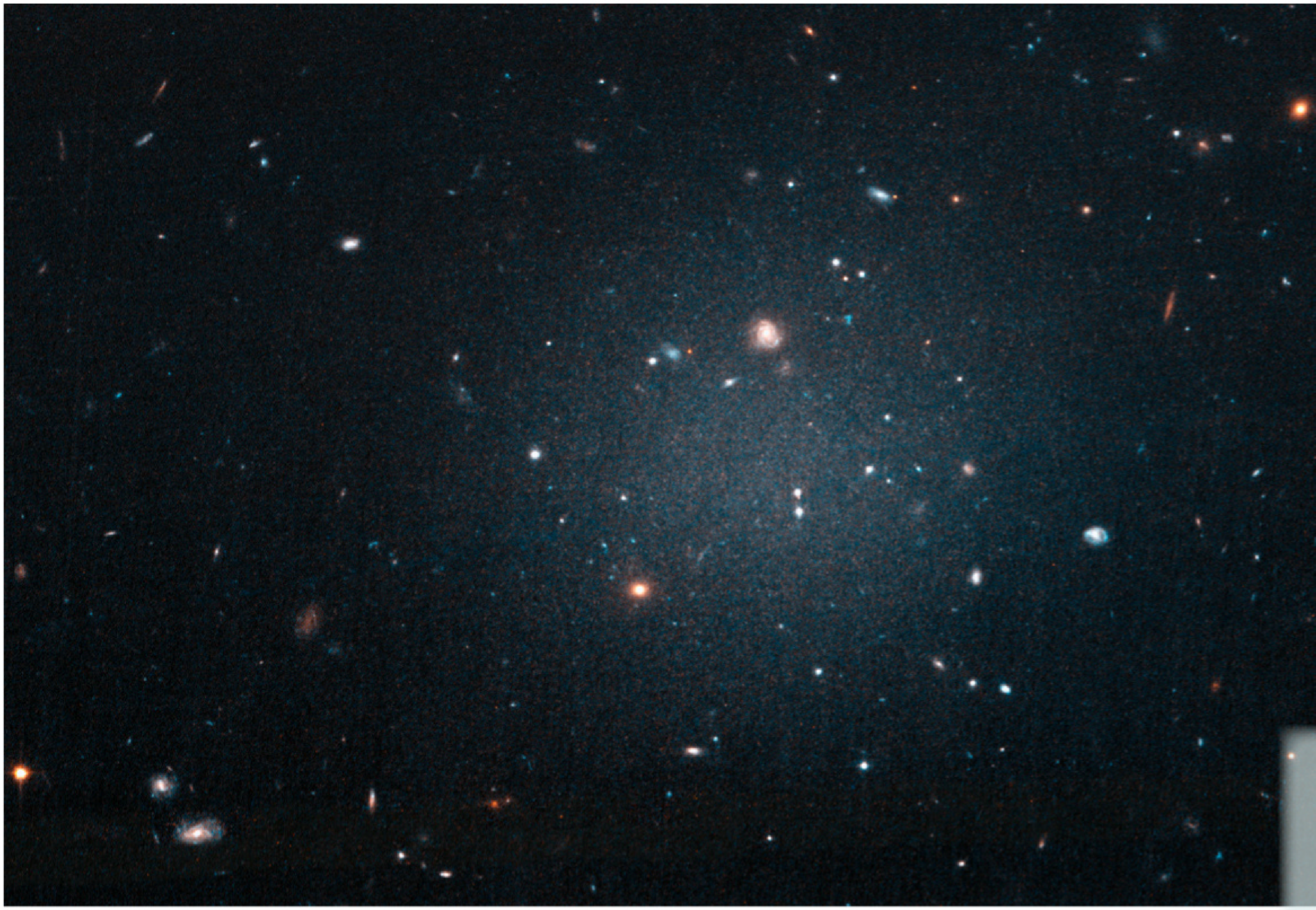
What is DF2?

DF2, the first known galaxy supposedly devoid of dark matter, is a member of a unique class of galaxies called ultra-diffuse galaxies (UDGs). Although UDGs can grow as large as the Milky Way, these hazy specters contain hundreds to thousands of times fewer stars. And because they're essentially transparent, they're extremely difficult for astronomers to observe in detail.

The relatively innocuous DF2 first stood out to researchers when they identified it using the Dragonfly Telephoto Array. This robotic collection of Canon 400mm telephoto lenses combine to



Astronomers uncovered two see-through galaxies that appear to be devoid of dark matter. And because they lack the strange substance, their globular clusters move much more slowly than expected. *ASTRONOMY*: ROEN KELLY



create a novel telescope that's particularly adept at imaging expansive and extremely faint structures. When the researchers observed DF2 with Dragonfly, they noticed the galaxy looked different than it did in images taken with the Sloan Digital Sky Survey (SDSS). In the Dragonfly images, DF2 looked like a blob of dim and diffuse light, but in the SDSS images, it appeared as a group of pointlike sources.

To investigate this discrepancy, van Dokkum's team went on to observe DF2 using the Advanced Camera for Surveys on the Hubble Space Telescope, and performed follow-up spectroscopic observations with the Keck Telescope.

"I spent an hour just staring at the Hubble image," said van Dokkum. "It's so rare, particularly these days after so many years of Hubble, that you get an image of something and you say, 'I've never seen that before.' This thing is astonishing — a gigantic blob that you can look through. It's so sparse that you see all of the galaxies behind it. It is literally a see-through galaxy."

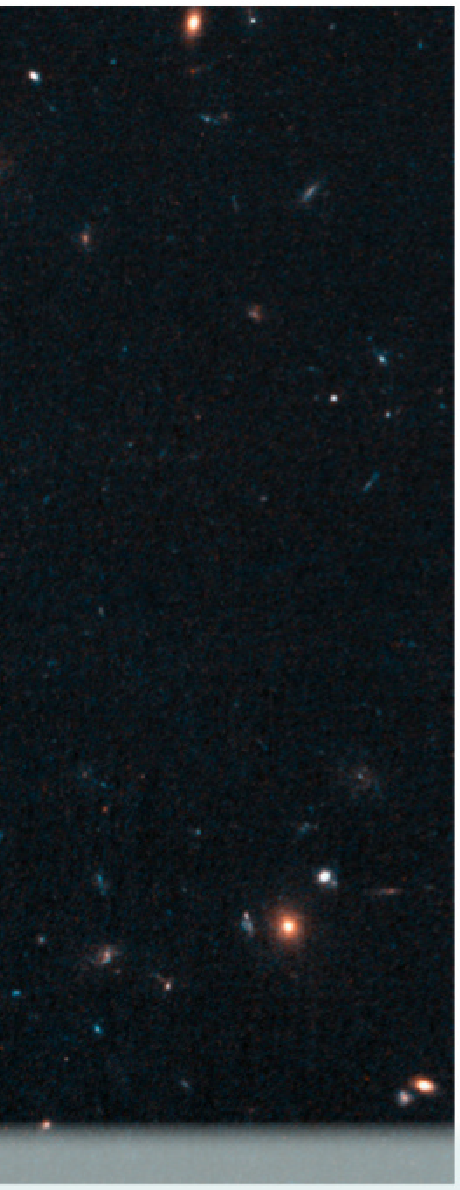
Using the Hubble data, van Dokkum and his team measured the galaxy's surface brightness fluctuations, which are a rudimentary distance indicator based on the fact that more distant galaxies appear more uniform in brightness. From this, the researchers calculated DF2 is located about 65 million light-years away.

> **“I spent an hour just staring at the Hubble image.”**
>
> **—Pieter van Dokkum**

Then, based on the Keck data, van Dokkum's team identified globular clusters (large, spherical groups of old stars) within DF2. Surprisingly, they found the globular clusters were moving at a snail's pace compared to what we would see if the galaxy were chock-full of dark matter. If DF2 had more dark matter, van Dokkum says, the increased gravitational pull would cause these clusters to move about three times faster than they do.

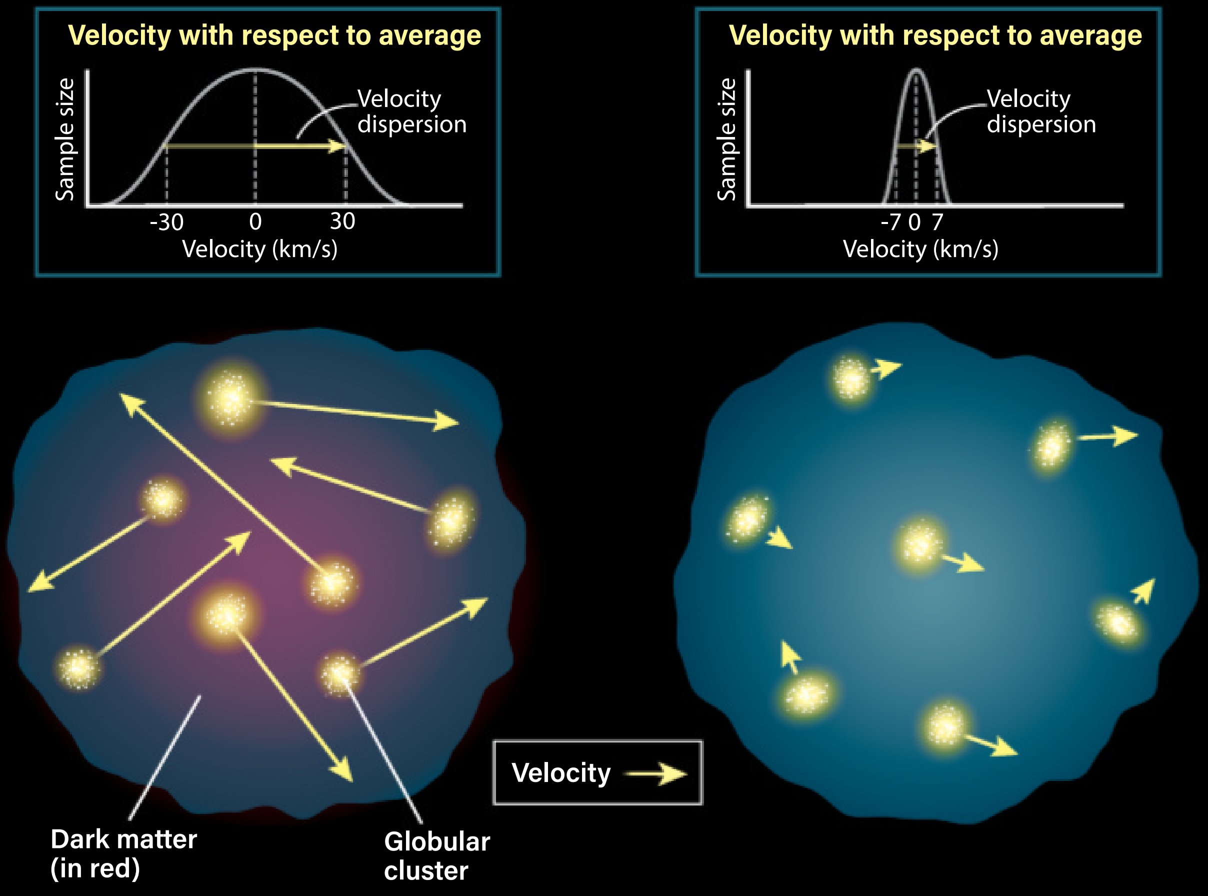
The realization that DF2 seems to have very little, if any, dark matter caught the researchers off guard because it's the first galaxy found lacking the pervasive material. "There is no theory that predicted these types of galaxies. The galaxy is a complete mystery, as everything about it is strange," said van Dokkum. "How you actually go about forming one of these things is completely unknown."

However, not everyone agrees that DF2 is missing its dark matter.



Hubble captured this beautiful image of the transparent galaxy DF2 with its Advanced Camera for Surveys. NASA/ESA/ P. VAN DOKKUM (YALE)

DARK MATTER'S EFFECT ON GLOBULARS



GALAXIES WITH DARK MATTER. In diffuse galaxies, globular star clusters typically do not orbit around their galaxies in circular paths like they do in spiral galaxies. Instead, they have a range of radial orbits that carry them every which way. If dark matter dominates a diffuse galaxy, the globulars within it should be moving relatively fast, as seen above.

ASTRONOMY: ROEN KELLY

GALAXIES WITHOUT DARK MATTER. However, in diffuse galaxies without dark matter, the lack of hidden mass means that globular clusters within the galaxies move much more slowly. In the case of DF2 and DF4, researchers found that the globulars are moving so slowly that the mass of the galaxies' visible matter alone is enough to account for their motions.

ASTRONOMY: ROEN KELLY

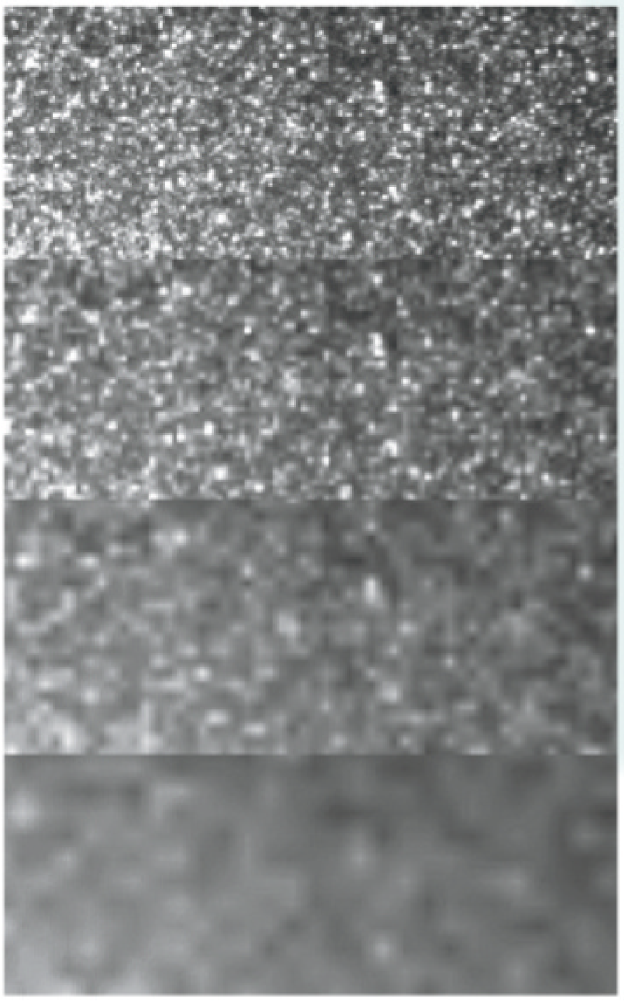
Debating DF2's distance

"Something that caught my attention very early on was the fact that the galaxy was not only anomalous for not having dark matter, but also for having an extraordinarily bright population of globular clusters," says Ignacio Trujillo of the Instituto de Astrofísica de Canarias, who led the main study challenging the bizarre nature of DF2. "I remember thinking: 'Two anomalies at the same time really looks odd.'" This led Trujillo to consider whether DF2 is really as distant as van Dokkum's team thinks.

If DF2 were roughly 65 million light-years away, like van Dokkum suspects, then it would be a strong candidate for the first example of a galaxy without dark matter. But Trujillo says that if DF2 is closer, the galaxy's observed properties would fall in line, more or less, with what's expected from your typical dark-matter-dominated galaxy.

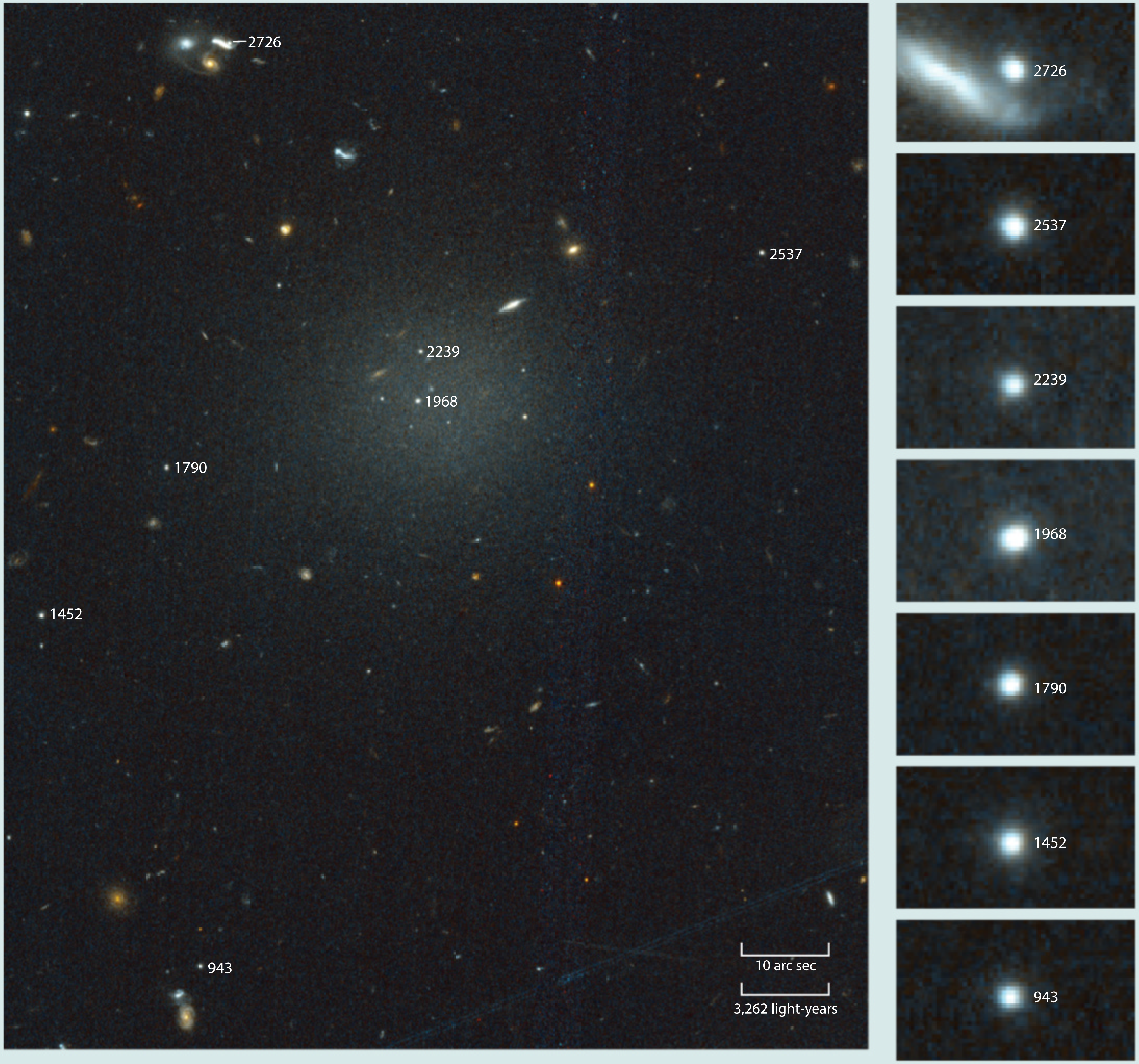
To test their theory, Trujillo and his team set off to independently determine the distance to DF2 using five different methods — all with varying degrees of trustworthiness.

Two of the methods relied on analyzing the brightnesses and sizes of DF2's globular clusters. According to the short-distance camp, if DF2 is closer than initially thought, then the galaxy's globular clusters no longer would be weirdly big and bright. Trujillo's team also compared DF2's properties to a



The basic idea of the surface brightness fluctuation method for determining distance is that the farther away a galaxy is, the smoother its overall brightness profile. This is because each pixel of an image contains a lot more stars for more distant galaxies. This image uses resampled Hubble data to show what M32 would look like at increasingly greater distances (nearest is at top, farthest is at bottom). NASA/ESA/W. KEEL (UNIVERSITY OF ALABAMA)

CLOCKING GLOBULAR CLUSTERS


2726
2537
2239
1968
1790
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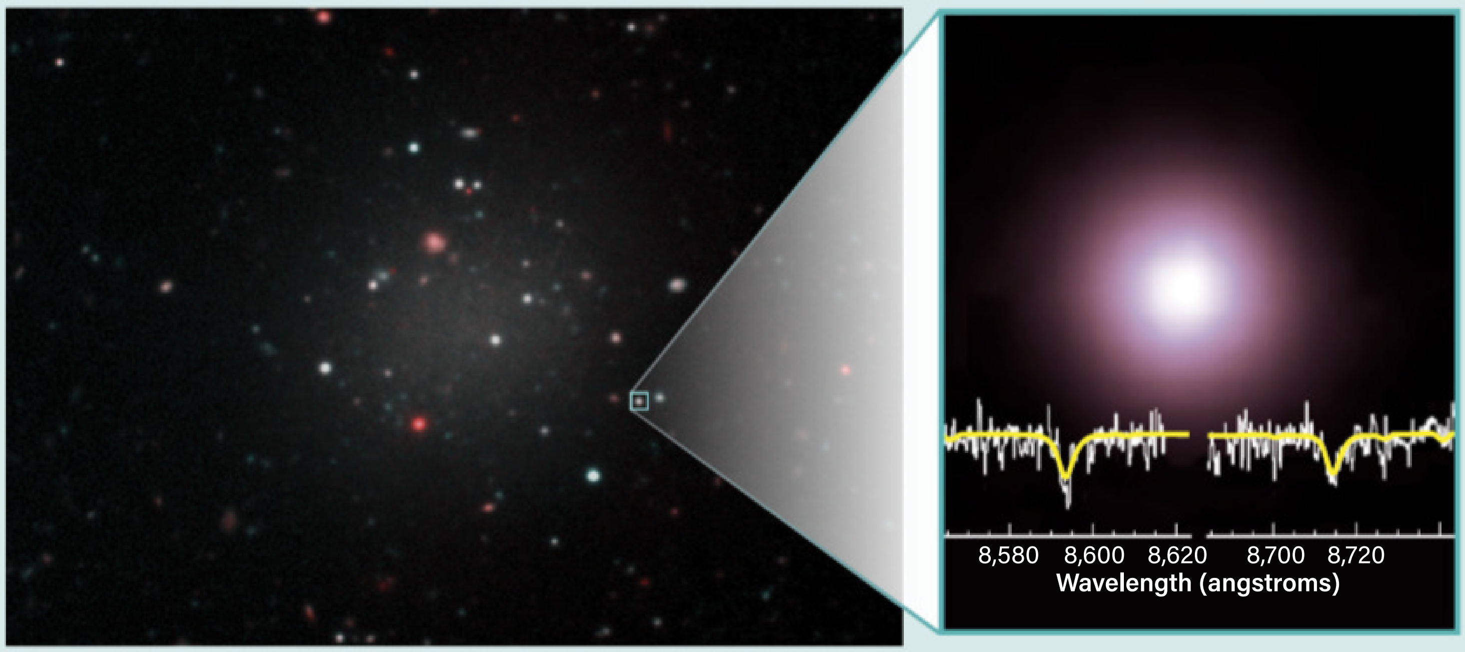
ABOVE: Shortly after determining galaxy DF2 is lacking dark matter, van Dokkum and his team identified another galaxy, DF4, that likewise seems to be missing the mysterious substance. The highlighted objects are DF4's globular clusters. VAN DOKKUM ET AL. (2019)

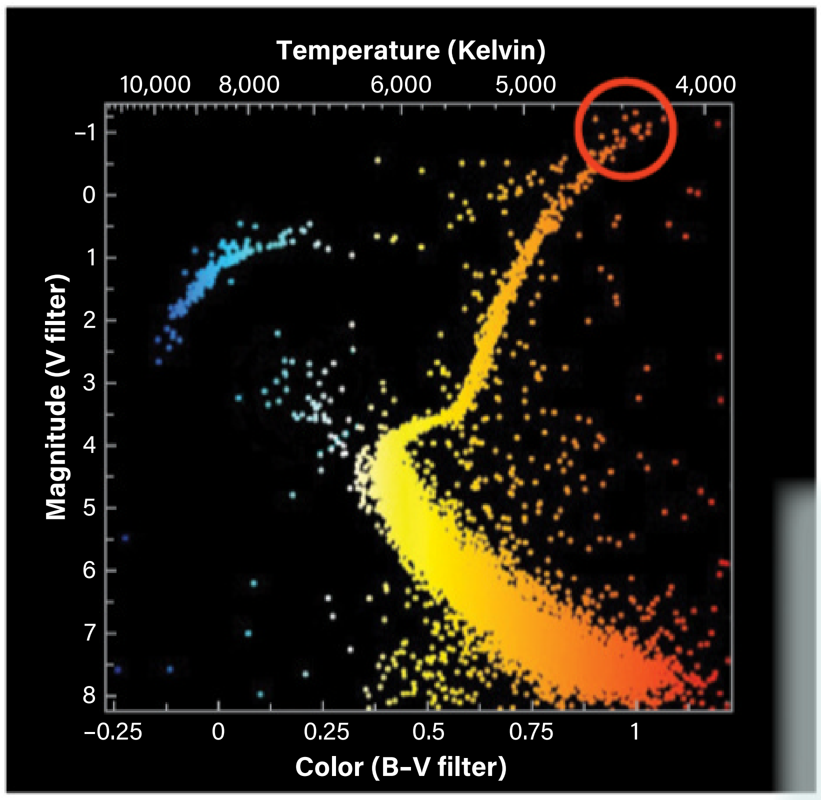


LEFT: To determine how quickly the globular clusters were moving in DF2, the researchers analyzed the absorption lines found in each globular cluster's spectrum. This revealed clues about the clusters' motions, and researchers then used this information to calculate the overall mass of the galaxy. GEMINI OBSERVATORY/NSF/AURA/W.M. KECK OBSERVATORY/JEN MILLER/JOY POLLARD similar galaxy, called DD044, which has a more reliable distance estimate, as well as recalculated DF2's distance using the same surface brightness fluctuation method (with different calibrations) as van Dokkum's team.

Finally, Trujillo's team analyzed the tip of the red giant branch (TRGB) in DF2's color-magnitude diagram, which plots the surface temperatures and luminosities of stars within a galaxy. Because the brightest red giant stars all shine with the same true brightness in infrared light, the only thing that should dramatically impact how bright they appear to us is their distance. So, by identifying how bright the stars on the TRGB look for a given galaxy, researchers can get a good grasp on how far away the galaxy really is.

"This is, by far, the most accurate way of measuring the distance to the galaxy if the data have good quality," Trujillo says. Based on all five methods, Trujillo and his team determined DF2 is likely only about 42 million light-years away, rather than some 65 million light-years away. This, Trujillo argues, would mean that DF2 isn't as strange as initially thought, and instead harbors about as much dark matter as you would expect from an average, run-of-the-mill galaxy.

> **"There is no theory that predicted these types of galaxies. The galaxy is a complete mystery, as everything about it is strange."**
>
> **—Pieter van Dokkum**



Stars at the tip of the red giant branch (circled in red) all shine with nearly the same intrinsic brightness when viewed in a certain band of light, despite differences in their composition or mass. So, if you measure how bright these stars appear, you can get a good estimate of their distance. *ASTRONOMY:* ROEN KELLY

But van Dokkum isn't convinced by this competing distance determination.

In August 2018, his team published yet another paper in response. In it, they argue Trujillo's "five 'independent measurements' are a bit misleading." For instance, van Dokkum says, "three of them are circular, in the sense that the authors argue that the properties of the galaxy would be less strange if it were at a closer distance." Plus, van Dokkum argues, the short-distance camp based their most convincing distance estimate on a "phantom" TRGB that's nearly twice as bright as the galaxy's true TRGB. This, van Dokkum says, led Trujillo's team to calculate a distance to DF2 that's only about 70 percent the actual value.

After showing why they think Trujillo's shorter distance to DF2 was due to blends in the TRGB data — where multiple stars were counted together as a single, bright red giant — van Dokkum's team went on to provide a new distance measurement to DF2 they claim is independent of calibration uncertainties. Their result: DF2 is about 61 million light-years away, which would mean DF2 still has a negligible amount of dark matter.

What about DF4?

But the debate didn't stop there.

After this academic back-and-forth, van Dokkum and his team found a second galaxy, DF4, which is nearly a clone of DF2 in terms of its size, surface brightness, morphology,

NASA/ESA/P. VAN DOKKUM (YALE)

HOW DID THESE GALAXIES FORM?

Although there is no generally accepted way to form a galaxy without dark matter, according to van Dokkum's initial paper on DF2, the team does have a few ideas about how it could have happened.

One possible scenario is that DF2 is actually a tidal dwarf galaxy. This type of galaxy can form during galactic mergers, which often fling out baryonic material — ordinary matter made of neutrons, protons, and electrons, such as stars and gas. However, DF2's composition isn't quite right: It appears to have fewer metals, or elements heavier than helium, than would be expected for a tidal dwarf galaxy.

Another option is that DF2 formed when winds from a nearby quasar swept together large clouds of low-metallicity gas, but the researchers point out that the see-through galaxy may be too diffuse for this to be a likely scenario.

Finally, the researchers suggest DF2 could have formed when clouds of gas — located in the space between nearby galaxies and flowing toward the suspected gravitational anchor of the galaxy group, NGC 1052 — broke away from the stream. Shocks in the gas, caused by jets from NGC 1052's central supermassive black hole, could have disrupted some of the flow, forming DF2. However, all of these are just hypotheses, and the researchers are working first to prove galaxies without dark matter really exist before diving into their origin stories. *—J.P.*

location, and distance. But, most importantly, DF4 likewise has an apparent dearth of dark matter.

Using the Keck Telescope to measure the motion and speed of DF4's diffuse gas, as well as seven of its globular clusters, van Dokkum's team calculated that DF4's distance is similar to DF2's — hovering around 65 million light-years away, give or take about 9 million light-years.

"We conclude that NGC 1052-DF2 is not an isolated case, but that a class of such objects exists," van Dokkum's team wrote in their DF4 discovery paper. "The origin of these large, faint galaxies with an excess of luminous globular clusters and an apparent lack of dark matter is, at present, not understood."

But, yet again, Trujillo and his team calculated their own distance to DF4. Based on Hubble data available at the time, they identified what they think is DF4's TRGB. This led them to conclude that DF4 is about 46 million light-years away, which would mean its globular clusters aren't actually that strange, and instead are pretty similar to those found in the Milky Way and elsewhere.

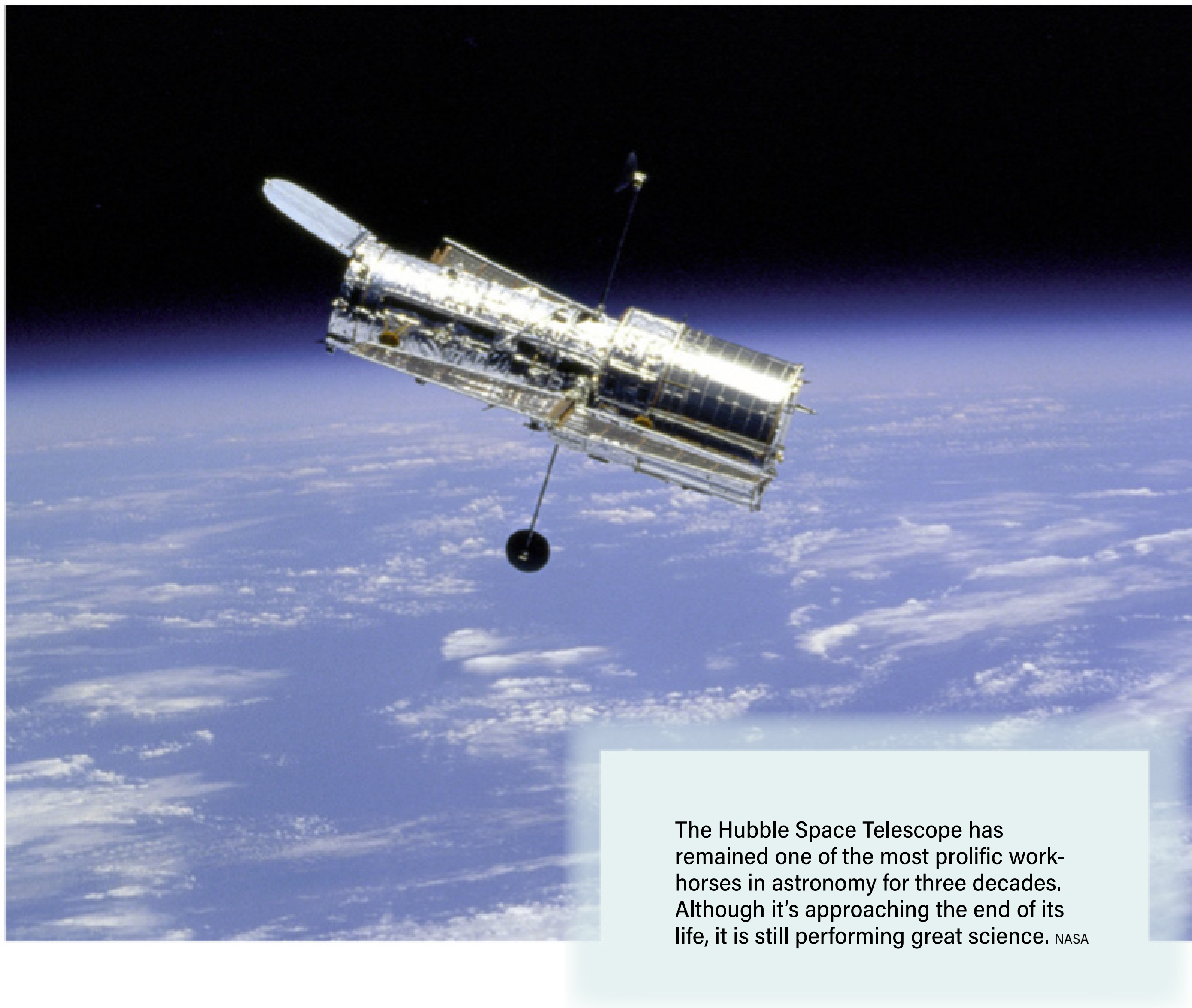
"All in all," Trujillo's team concluded in their response paper, "the proposition that both NGC 1052-DF2 and NGC 1052-DF4 are 'missing dark matter' is still far from being placed on sure footing."

Hubble takes another look

In the summer of 2019, in order to determine whether Trujillo's team had identified DF4's true TRGB, van Dokkum's group used Hubble's keen eye to collect new, deep images of DF4. On October 16, they posted another paper, which has been submitted to *The Astrophysical Journal Letters,* on the preprint site arXiv. Based on the fresh Hubble data, which picked up many more, much fainter stars, the paper claims the short-distance camp again misidentified DF4's brightest red giant stars, leading to a closer derived distance.

"In the new data, there really is no ambiguity," says study author Shany Danieli of Yale, who is van Dokkum's colleague. "We think the new data really rule out the [shorter-distance] option."

"I think this is definitive," says van Dokkum. "The TRGB cannot be argued with: It is caused by well-understood stellar physics, and [is] as direct as distance indicators get."



The Hubble Space Telescope has remained one of the most prolific workhorses in astronomy for three decades. Although it's approaching the end of its life, it is still performing great science. NASA

> **"I remain enormously skeptical about their outcome of a long distance for DF4."**
>
> —Ignacio Trujillo

"I remain enormously skeptical about their outcome of a long distance for DF4," Trujillo said after reviewing the preprint of the paper. After the peer-reviewed version was published in May of 2020, Trujillo added, "I remain equally skeptical. I was approached by the editor of the journal and I suggest[ed] a number of tests to check the robustness of the analysis, but none of those were addressed in this accepted version. Therefore, I continue having the same concerns."

Then there's also the matter of how van Dokkum's long-distance camp selected which of DF4's stars they would include in their TRGB analysis, which is yet another point of contention. "I think there are a number of choices [van Dokkum's group] have used that have not been justified," Trujillo says. "All of these choices seem to be selected to favor a larger distance than what the data suggests."

One such choice, Trujillo explains, is that the quality cuts van Dokkum's team used to pick which stars were included in their analysis seem to ignore many stars. Another, he adds, is that van Dokkum's team made "a preselection of their stars based on the colors" and they do not explain why or how that impacts their outcome. Both of these choices, Trujillo says, could greatly impact the derived distance to DF4.

What's next?

So, at this stage, the answer to whether DF2 and DF4 have dark matter or not is still largely up in the air.

ABOVE: After imaging DF2 and DF4 with the Dragonfly Telephoto Array, scientists used Keck Telescope in Hawaii to spectroscopically measure the velocity of the galaxies' globular clusters, revealing they lack dark matter. NASA/JPL

LEFT: The Bullet Cluster exemplifies how dark matter is a separable substance. As two giant galaxy clusters collided, normal matter (pink) was trapped between non-interacting clouds of dark matter (blue). NASA/CXC/M. WEISS

New research published November 25, 2019, in *Nature Astronomy* reported the discovery of 19 dwarf galaxies that likewise seem to be severely lacking in dark matter.

However, no matter what's really going with these galaxies without dark matter, van Dokkum says, "The broader point is that these are fascinating galaxies, and all aspects of our findings should certainly be questioned and scrutinized."

So if these latest results hold up to the scrutiny that's likely to come, then finding galaxies missing dark matter would completely change our understanding of how we think galaxies form and evolve.

"The galaxies point to an alternative channel for building galaxies — and they even raise the question whether we understand what a galaxy is," says van Dokkum. Right now, we think that galaxies begin with dark matter, which is how they're able to gravitationally attract the massive amounts of gas and dust needed to kick-start star formation.

"The thing is, we have no idea how star formation would proceed in the absence of dark matter," van Dokkum says. "All we can say is that there must have been very dense gas early on in their history," otherwise, galaxies without dark matter couldn't create new stars.

But is this latest distance determination to DF4 really robust enough to start exploring the implications of finding a galaxy without dark matter?

"Yes, that's our hope. We'd love to move to discuss what these galaxies mean, rather than whether our measurements were correct," Danieli says.

"That said," she adds, "we fully agree with everyone that 'extraordinary claims require extraordinary evidence.'"

Associate Editor **Jake Parks** *has long been fascinated by dark matter, and looks forward to learning more about the mysterious substance in the years and decades to come.*

GALAXY CLUSTERS The universe's

Abell 2744 in Sculptor was the first of six massive galaxy clusters astronomers targeted with the Hubble Space Telescope as part of its Frontier Fields program. Packed with luminous galaxies and invisible dark matter, these clusters magnify the remote universe to give scientists their best views of the early cosmos. NASA/ESA/THE HST FRONTIER FIELDS TEAM (STScI)

With Hubble's superb optics and gravity's magnifying power, astronomers are opening a new frontier at the edge of the universe.

by Liz Kruesi

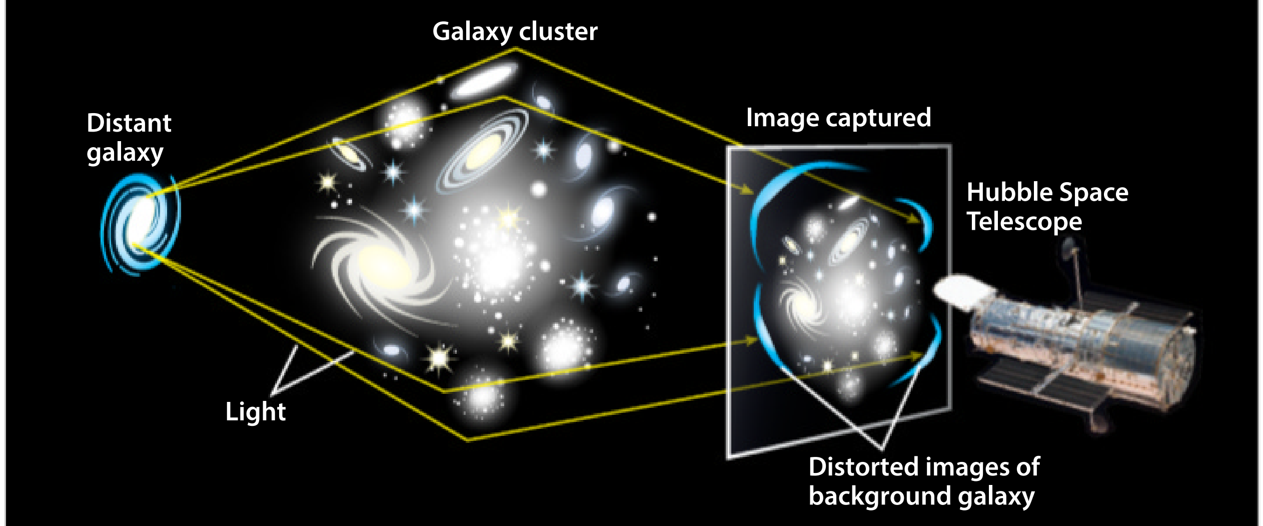
IT ALL STARTED with a simple idea. In 2012, Matt Mountain was the director of the Space Telescope Science Institute (STScI), the organization that manages the Hubble Space Telescope. He tasked a group of a dozen astronomers to come up with an observing project for the orbiting telescope that could reveal new insights into galaxy formation and the early universe.

Many times before, scientists had pointed Hubble to seemingly empty patches of sky — small areas with no Milky Way stars — and collected light for several days. In these so-called deep fields, the space telescope revealed thousands of galaxies reaching to the edge of what humans could detect. It wasn't a stretch to imagine that if every tiny, blank field of sky holds thousands of galaxies, our home Milky Way must be just one of a trillion or more of them.

But what other awe-inspiring discoveries could Hubble make about the distant and early universe? One idea put forth in the group was to combine the observing power of Hubble, one of humanity's finest telescopes, with the magnifying power of enormous clusters of galaxies. Through a trick of gravity, such clusters magnify objects behind them. Each scientist in the group proposed an idea, and the astronomers discussed all of them one by one, says Yale University's Priyamvada Natarajan. She was the sole group member studying galaxy clusters. "I made the case for these clusters, and I was super excited when people agreed that that might be worth a shot."

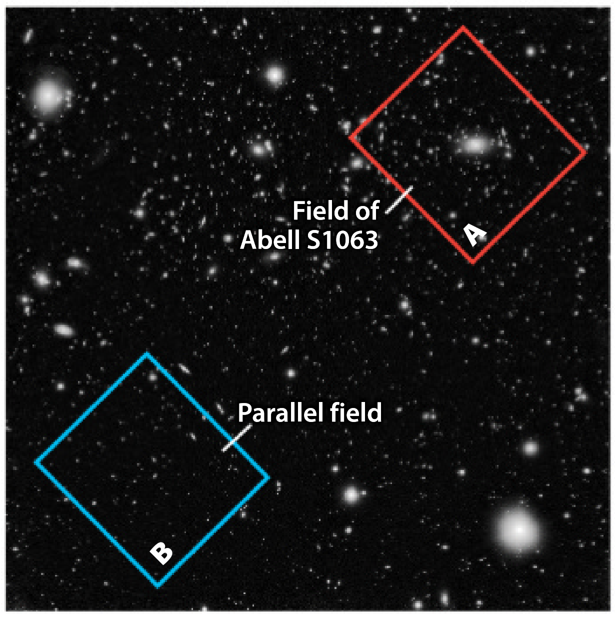
And so in December 2012, the Hubble Frontier Fields (HFF) program was born. It uses more than 2 million seconds of Hubble observations — precious observing time for the aging telescope — to study six galaxy clusters as well as six "blank fields," one near each cluster. Hubble completed the observations in late 2016, and astronomers have already mapped dark matter in these clusters and revealed hundreds of the universe's first galaxies. But they expect many more discoveries to come in the years ahead.

How gravitational lensing works

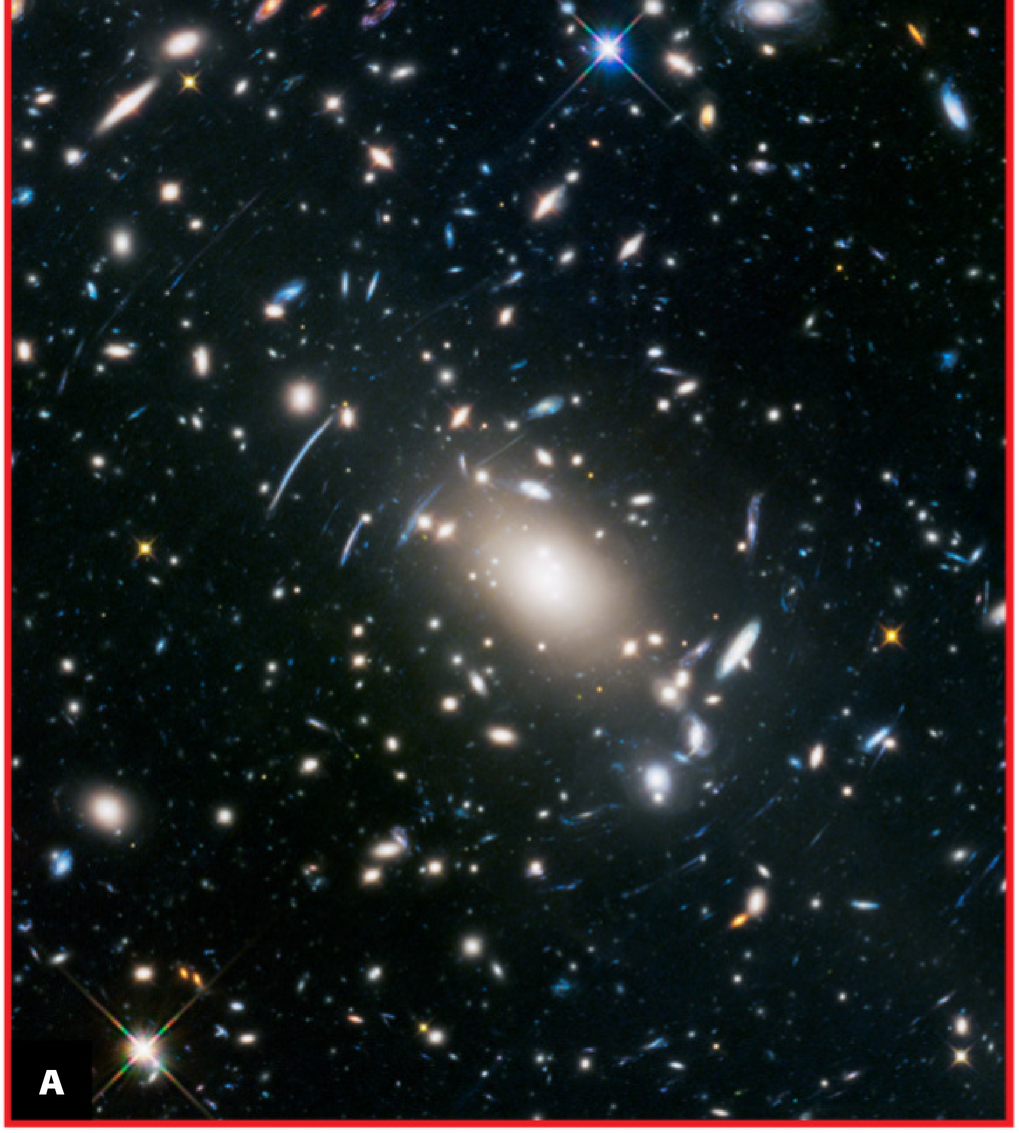


When light from a distant galaxy passes through a massive galaxy cluster, the cluster acts like a giant lens that bends, amplifies, and warps the light, often producing several distorted images of the background galaxy. *ASTRONOMY*: ROEN KELLY

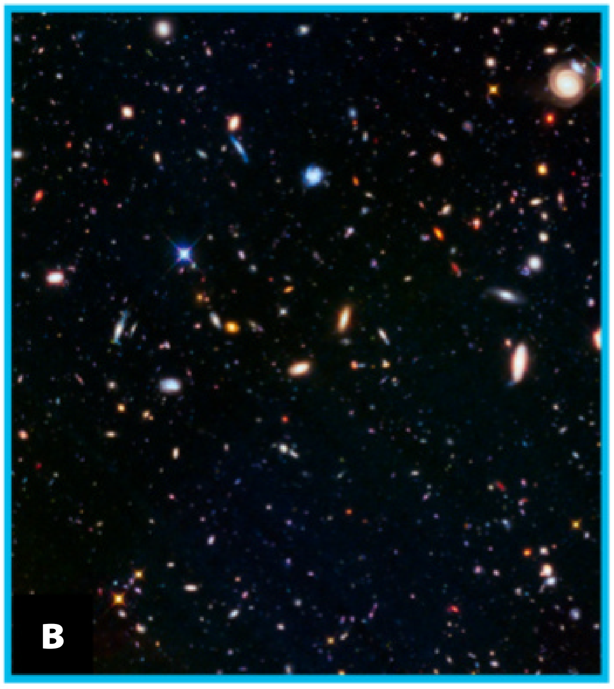
cosmic lenses



While Hubble observes a Frontier Field with the infrared Wide Field Camera 3, it simultaneously views a nearby parallel field with its visible-light Advanced Camera for Surveys. (This graphic shows the Abell S1063 Frontier Field and its parallel field.) Six months later, when the orbiting observatory returns to the same field, the camera footprints have swapped places. In this way, astronomers build up images that combine infrared and visible light. G. BRAMMER, D. MARCHESINI, ET AL. (2016)



(A) The gravitational lens created by galaxy cluster Abell S1063 in Grus not only magnifies the light from more distant objects, but also distorts their appearance. This warping, similar to the effect of a funhouse mirror, turns many background galaxies into arcs and streaks. NASA/ESA/J. LOTZ (STScI)



(B) The parallel field to Abell S1063 contains only a few foreground stars in the Milky Way (the objects with four bright spikes radiating from them). Galaxies of all shapes, sizes, and distances litter the rest of the field. Such images allow astronomers to compare six new "blank" fields with Hubble's previous deep fields. NASA/ESA/J. LOTZ (STScI)

Cosmic conglomerations

The magnifying power of a cluster of galaxies results from the gravitational force it exerts. A galaxy cluster holds hundreds to thousands of galaxies, all bound by gravity. Look at a cluster with X-ray eyes, and you'll see tenuous gas, glowing at millions of degrees, between the galaxies. If you could see only the cluster's gravitational field, you would detect a huge amount of invisible material clumping around the individual galaxies and denting the fabric of space-time. This "dark matter" is the glue that holds all the galaxies and gas together; it makes up some 80 to 90 percent of the cluster's mass. And that total mass is enormous: A galaxy cluster holds hundreds to thousands of trillions of times the mass of our Sun. That's a 1 followed by 14 or 15 zeros.

This incredible mass warps space-time, causing the cluster to act like a lens and affecting the paths that light follows as it passes by. Have you ever looked through an antique glass window? Some areas have more glass than others, so the light flowing through it doesn't follow a straight line. Objects on the other side of the window look distorted. In the same way, if a galaxy lies behind a galaxy cluster, its light will bend as it passes through the dented space-time around the cluster. In fact, light from a background source can follow multiple paths around the cluster. And so, our telescopes see multiple distorted images of the background galaxy.

But the galaxy cluster doesn't just warp the light, it also magnifies it. And it's this aspect that the HFF program really exploits: magnifying the light of background sources such as galaxies and exploding stars. These existed further back in time, so astronomers can use the HFF clusters to study faint objects from the early universe.

The fields next door

Whereas a typical backyard telescope funnels light into only one instrument — your eye, a camera, or some other type of detector — Hubble doesn't have the same limitation. The space telescope has five scientific instruments that can analyze the light the primary mirror directs to the focal plane. "Within the focal plane, the fields of view of individual cameras are at slightly different places," says Jennifer Lotz, the HFF lead scientist and an astronomer at STScI. "When you have our infrared camera, WFC3 [Wide Field Camera 3], pointed in the center of the cluster, the other cameras are pointed at different places sort of offset from that around that central pointing."

The HFF scientists use this to their advantage. They turn on two cameras — the WFC3 to capture infrared light and the Advanced Camera for Surveys (ACS) to collect visible light — to observe a galaxy cluster and a nearby "blank" field at the same time. Astronomers use these blank fields like the previously studied deep fields, to peer at seemingly empty portions of the sky. "We're trying to use Hubble in a very efficient mode, where we're turning on two cameras at once," says Lotz.

They hold Hubble's position — with WFC3 focused on the galaxy cluster and ACS observing the blank field — for 70 orbits around Earth. Because the telescope slips behind our planet during about half of each orbit, the total observing time with this configuration equals 280 exposures, each 15 to 20 minutes.

"Because we need to obtain both optical and infrared observations, on both the cluster and the blank field, this means we need to observe them again with Hubble rotated so that the cameras are 'flipped' around," says STScI's Anton Koekemoer, who is in charge of the team that produces all the science-quality Hubble images for the HFF project. "This typically is only possible after a few months."

Returning to the same field of view several months later has another advantage: Astronomers can spot any differences between the two observing epochs. Those changes could be caused by a stellar flare or an exploding star (a supernova), which can lead to even more discoveries.

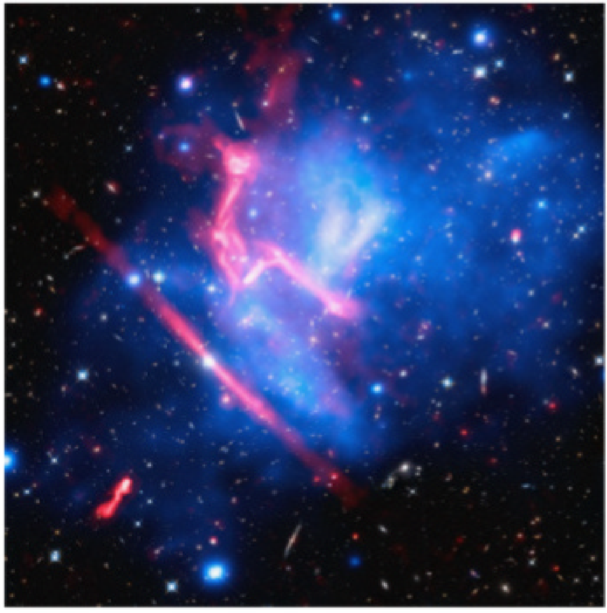
Modeling the prescription

Astronomers liken the six galaxy clusters to eyeglasses with lumpy lenses. To understand what they see behind each cluster, they need to know the lens' prescription. This takes several teams of researchers to map the distribution of material within each cluster, something possible only with the fine eye of Hubble and thorough theoretical models of how dark matter behaves.

The first step in building a model of the lens is to identify any and all warped images — which typically look like arcs or smears — from each background object. The human brain finds these better than any computer program does, so researchers must inspect every HFF image.

Then, they run a computer program to match the positions of these warped images. Seven different teams of researchers have written software to accomplish this goal. At its most basic, a program knows that clumps of invisible dark matter will surround and lie near the cluster's member galaxies. Researchers also have to enter information about how far away the background sources that appear as multiple images lie. The software varies the amounts and positions of dark matter slightly to reconstruct what astronomers see on the sky. "Once I manage to get all of these multiple images at their real positions, meaning the observed positions on the Hubble images, then the mass distribution should be correct," says Mathilde Jauzac of Durham University in the U.K., a member of one of the lensing-map teams.

Galaxy cluster MACS J0717.5+3745 in Auriga is the largest gravitational lens not just among the Frontier Fields clusters, but also in the known universe. This massive conglomeration of galaxies and dark matter appears to contain at least four merging subclusters. NASA/ESA/THE HST FRONTIER FIELDS TEAM (STScI)



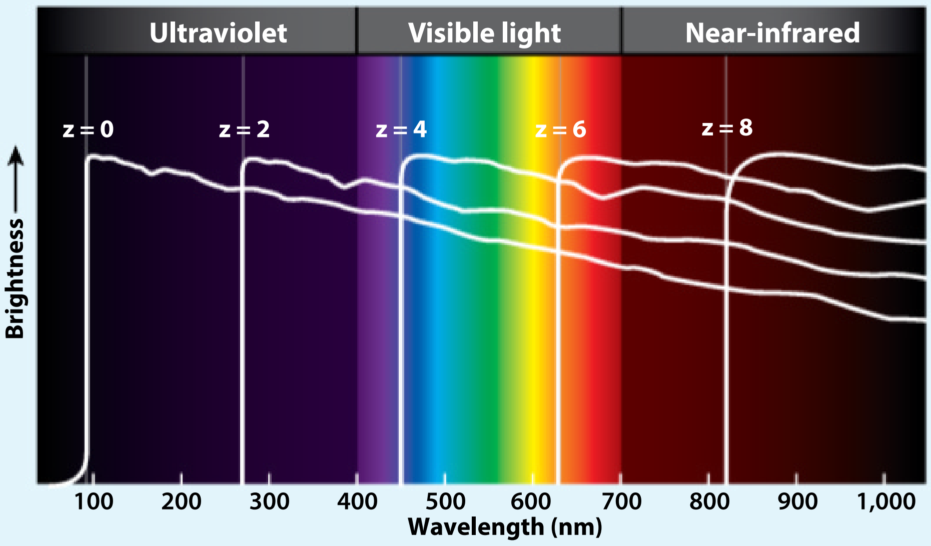
This multiwavelength view of MACS J0717.5+3745 combines visible light (red, green, and blue) with X-rays (diffuse blue glow) and radio waves (diffuse pink glow). Shock waves from multiple collisions cause the large radio arcs, while the clumpy X-ray emission reflects the four subclusters now merging. X-RAY: NASA/CXC/SAO/R. VAN WEEREN ET AL.; OPTICAL: NASA/STScI; RADIO: NRAO/AUI/NSF

Jauzac, along with other scientists involved with the HFF project, uses these lensing maps, the Hubble photographs, and data collected with other telescopes to study the dynamics within the galaxy clusters. Other researchers use the maps to interpret where dark matter sits within the clusters and how it behaves.

But the lens models are also crucial for the researchers studying what lies *behind* the galaxy clusters. "Knowing the lensing magnification allows scientists who study the background universe to connect the observed properties of the faraway galaxies with their intrinsic ones: their luminosities, star formation rate, stellar mass, et cetera," says the University of Michigan's Keren Sharon, who leads another lensing-model team.

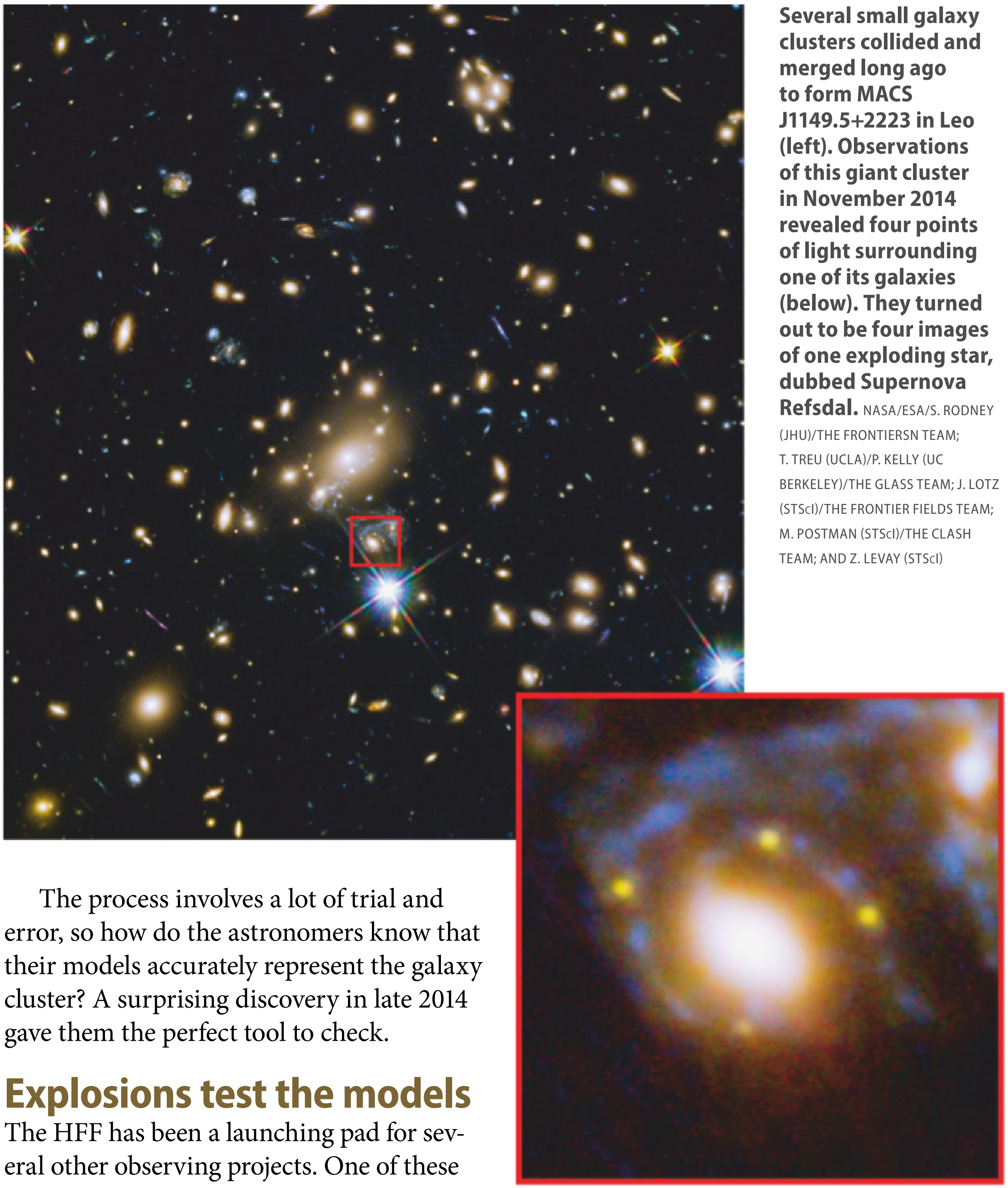
In fact, one requirement of HFF when the project began was for six chosen teams to provide the rest of the astronomical community with their lensing-map algorithms using Hubble data that already existed. As the project progressed, the teams have changed slightly (now there are seven), and each team releases updated versions of its model as it incorporates newer HFF images. Although Hubble wrapped up the imaging for the project with its final photos of Abell 370 in late 2016, it takes time to analyze all the data and run the lensing models. Researchers have final models for the clusters Abell 2744, MACS J0416.1–2403, and MACS J0717.5+3745, including MACS J1149.5+2223, Abell S1063, and Abell 370.

Zeroing in on distant galaxies



Neutral hydrogen absorbs most light with wavelengths shorter than 91.2 nanometers, so a galaxy's spectrum shows a sharp break there. Cosmic expansion creates a redshift (z) that moves this break to a longer wavelength, so remote objects show up at longer wavelengths and not shorter ones. The wavelength at which an object disappears gives a good estimate of its distance.

ASTRONOMY: ROEN KELLY



Several small galaxy clusters collided and merged long ago to form MACS J1149.5+2223 in Leo (left). Observations of this giant cluster in November 2014 revealed four points of light surrounding one of its galaxies (below). They turned out to be four images of one exploding star, dubbed Supernova Refsdal. NASA/ESA/S. RODNEY (JHU)/THE FRONTIERSN TEAM; T. TREU (UCLA)/P. KELLY (UC BERKELEY)/THE GLASS TEAM; J. LOTZ (STScI)/THE FRONTIER FIELDS TEAM; M. POSTMAN (STScI)/THE CLASH TEAM; AND Z. LEVAY (STScI)

The process involves a lot of trial and error, so how do the astronomers know that their models accurately represent the galaxy cluster? A surprising discovery in late 2014 gave them the perfect tool to check.

Explosions test the models

The HFF has been a launching pad for several other observing projects. One of these is the Grism Lens-Amplified Survey from Space (GLASS), which uses Hubble to collect detailed spectra on galaxies lying behind the six Frontier Fields clusters and four other massive clusters. A few members of the GLASS team also have an interest in searching for supernovae, the brilliant explosive deaths of stars, behind the clusters.

To find these, GLASS astronomers take photographs of the same galaxy cluster weeks apart. Then, they subtract the new image from the old one, getting rid of anything that doesn't change over that time period, such as galaxies in the cluster or in the background. "We take these beautiful HST images, and we get rid of all the beauty," says Steven Rodney of the University of South Carolina. "But if anything has changed — meaning, a star has exploded in the interim — that supernova will appear as a bright point of light on our image."

While comparing GLASS images of MACS J1149.5+2223 taken November 3, 7, 10, and 11, 2014, Rodney's colleague Patrick Kelly immediately saw three points of light in the subtraction images. "The shock of that discovery was immediately obvious," adds Rodney. They knew they had found something unique and incredible. Astronomers usually see a supernova as a single point of light, but three meant they had found a multiply lensed supernova — something never seen before.

And the timing couldn't have been any better. On November 20, Hubble would look again at this galaxy cluster for its 70-orbit HFF observations. When Kelly, Rodney, and their collaborators incorporated the first few HFF images taken November 20, those three points of light instead had become four.

The supernova resides in the arm of a spiral galaxy that lies far behind the galaxy cluster, and the explosion's light took four paths through the cluster's warped spacetime. They named the object Supernova Refsdal after Norwegian astrophysicist Sjur Refsdal, who 50 years earlier had theorized that a supernova could be lensed into multiple images.

Because each path has a slightly different length, light takes a different amount of time to traverse each one. A supernova always brightens rapidly and then fades away. Kelly, Rodney, and their team watched how the brightness changed from November 3 to 20, and from the slight differences, astronomers were able to refine their maps of the mass distribution in MACS J1149.5+2223. "To be able to understand what we're seeing behind these clusters, you have to trust that these lens models are correct," says Rodney.

A SPECIAL KIND OF SUPERNOVA

The multiply lensed Supernova Refsdal was a spectacular find, but what would be even more helpful is a multiply lensed type Ia supernova. This type of blast — in which a white dwarf in a binary system explodes — has an easy-to-calibrate intrinsic brightness. Thus, when astronomers find one and watch how its light evolves, they can calculate what its maximum brightness was.

"Then we say, 'Well, it looks to be much brighter than that by a specific amount that we can measure, and the amount that it's been brightened gives us an exact measure of the magnification,'" says Steven Rodney, who leads a follow-up survey to study supernovae discovered in the Hubble Frontier Fields project. "We can compare that measurement to what the models for the dark matter of the cluster suggest."

With that information, they can figure out how much the gravitational lens of the galaxy cluster magnifies the light. "It's a bit like we're taking these lenses to the eye doctor and checking the prescription," says Rodney. So far, his team has found one lensed type Ia supernova in the Frontier Fields, but it wasn't multiply lensed. —*L.K.*

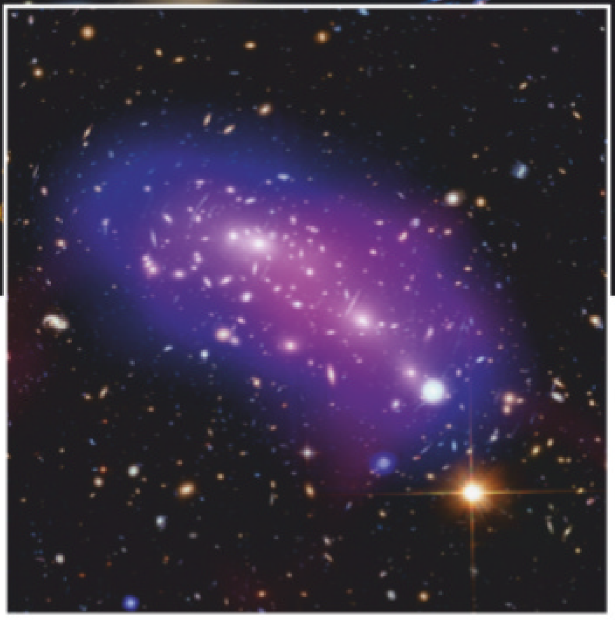
The lensing-map teams provided more than trust, however, when they predicted a fifth image of SN Refsdal likely would appear in the following year. Jauzac's team in particular estimated it would show up between November 2015 and January 2016.

And on December 11, 2015, a fifth image appeared. "That was the first time we could actually prove to the entire community … that actually lensing works, lensing is useful, and we can rely on lensing," Jauzac says.

To the faint edge

Other teams of researchers use the magnifying power of the HFF galaxy clusters to hunt down the faintest galaxies from the early universe. Although these objects had been theorized, no one had ever seen them because of their feeble light.

Observations of galaxy cluster MACS J0416.1–2403 in Eridanus, along with MACS J0717.5+3745 and Abell 2744, have turned up hundreds of galaxies from when the universe was just 600 million to 900 million years old. NASA/ESA/THE HST FRONTIER FIELDS TEAM (STScI)



X-ray emission (diffuse blue glow) and radio radiation (diffuse pink glow) nearly coincide in MACS J0416.1–2403, shown here with a Hubble visible-light image (red, green, and blue). Astronomers interpret the large X-ray and radio overlap (which appears purple) to mean that the subclusters have just started to collide. X-RAY: NASA/CXC/SAO/G. OGREAN ET AL.; OPTICAL: NASA/STScI; RADIO: NRAO/AUI/NSF

Neutral hydrogen gas filled the early cosmos, with each atom holding one proton and one electron. But the first stars, which lived in these faint dwarf galaxies, burned hot and bright, shedding copious amounts of ultraviolet light. This energetic radiation kicked the electrons out of the hydrogen atoms, turning the universe into a sea of ionized gas. Thus, these first stars cleared the opaque neutral hydrogen like the morning Sun burns off fog. (Because the cosmos also was ionized in its first 380,000 years, astronomers call the first-stars-led process "reionization.")

While the theory of reionization *seemed* sound, scientists had not detected enough early dwarf galaxies to explain the ionization of the entire universe. "We needed to account for fainter galaxies, which we suspected to be more abundant," says Yale University's Hakim Atek. "Thanks to the Frontier Fields clusters, we were able to push this detection limit." He adds that the galaxy clusters magnified the light from these faint galaxies by a factor of about 30.

Atek, who was at Switzerland's Ecole Polytechnique Fédérale de Lausanne at the time of the study, led the discovery of these galaxies and the work estimating their ultraviolet emission. The astronomers found some 250 dwarf galaxies behind three clusters — Abell 2744, MACS J0416.1–2403, and MACS J0717.5+3745 — and their parallel blank fields.

Many forms of light

Another mode of discovery involves combining the Hubble images with data from several additional telescopes. "Multiwavelength observations are the only way to get a complete picture of a cluster," says Stanford University's Georgiana Ogrean, who studies the dynamics of galaxy clusters.

Astronomers are observing the six galaxy clusters with the infrared-sensitive Spitzer Space Telescope, collecting about 100 hours of images for each cluster. The light that Spitzer detects comes from objects glowing at cooler temperatures than what Hubble sees.

With infrared and visible light, astronomers can see dust and stars, but what about the gas within each cluster? That's where the space-based Chandra X-ray Observatory and XMM-Newton come in. They capture the glow of hot gas in addition to some galaxies and stars.

Another project that builds off the HFF program uses Hubble to capture ultraviolet light, which reveals hot, young stars. Astronomers also use ground-based radio telescopes to see star-forming galaxies, the centers of active galaxies, and diffuse radio sources in the fields.

By combining multiple types of radiation, Ogrean and her colleagues have performed detailed studies on three of the HFF galaxy clusters. They have found that MACS J1149.5+2223 is the remnant of smaller clusters that collided and merged long ago; MACS J0416.1–2403 is in the early stages of a merger; and MACS J0717.5+3745 "is the most complex merging system known, consisting of at least four merging subclusters," she says.

Several other teams also combine different types of light to learn about the clusters themselves. And there are other creative ways that astronomers are using the HFF images to scour the cosmos. In fact, so far more than 90 papers using the project's data have been published in scientific journals, and these are just the first analyses of the HFF images.

"Yes, the pictures are pretty," says Sharon, "but what is really beautiful is that when you identify the lensing evidence in your data and plug it in the right equations, you can really see physics in action. I feel lucky to live in a time where our technology allows these phenomena to be routinely measured."

In the years to come, astronomers will continue to advance their understanding of what's happening within each cluster, and to tease out even more clues about what lies behind.

Liz Kruesi *writes about the universe from Denver, Colorado.*

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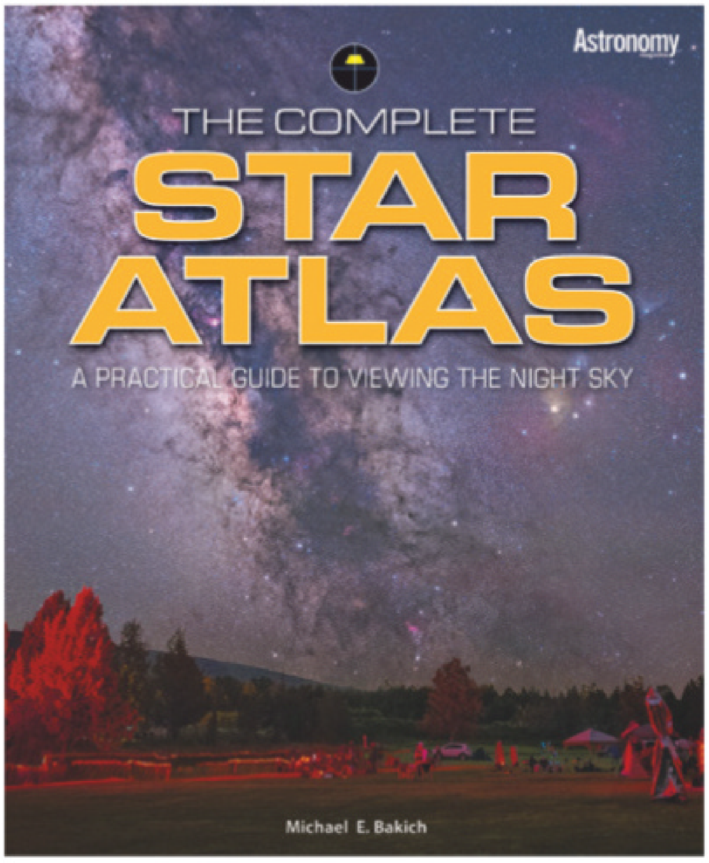

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